NASA/TM—1998–208533

IN-13
358277
p.162



Interplanetary Mission Design Handbook:
Earth-to-Mars Mission Opportunities and Mars-to-Earth Return Opportunities 2009–2024

L.E. George
U.S. Air Force Academy, Colorado Springs, Colorado

L.D. Kos
Marshall Space Flight Center, Marshall Space Flight Center, Alabama

July 1998

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L.E. George
U.S. Air Force Academy, Colorado Springs, Colorado

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Marshall Space Flight Center, Marshall Space Flight Center, Alabama

National Aeronautics and
Space Administration

Marshall Space Flight Center

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Acknowledgments

Jerry R. Horsewood, Adasoft, Inc., and
Andrey B. Sergeyevsky, NASA Jet Propulsion Laboratory

Available from:

NASA Center for AeroSpace Information
800 Elkridge Landing Road
Linthicum Heights, MD 21090–2934
(301) 621–0390

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
(703) 487–4650

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DEFINITION OF SYMBOLS AND ABBREVIATIONS

a	semimajor axis (km)
cnj	Conjunction Class Mission
C_3	energy (km^2/sec^2)
ΔV	Delta Velocity (km/sec)
DRM	Design reference mission (two 2011 cargo/one 2014 piloted flight)
e	orbit eccentricity
ε	orbit energy (km^2/s^2)
ECRV	Earth crew return vehicle
HIHTOP	Heliocentric Interplanetary High-Thrust Trajectory Optimization Program (the MAnE optimization module)
LEO	low-Earth orbit (assumed 400-km altitude)
MAnE	Mission Analysis Environment (for Heliocentric High-Thrust Missions (Adasoft, Inc. tool))
mt	metric ton, or 1,000 kg
RCS	Reaction Control System
SWISTO	Swingby-Stopover Trajectory Optimization Program
TEI	trans-Earth injection
TMI	trans-Mars injection
TOF	time of flight
T/W	thrust-to-weight
$V\infty$	V infinity, or departure hyperbolic excess velocity (km/sec)
lox/CH_4	liquid oxygen/methane
R_p	radius of perigee
R_a	radius of apogee
υ	true anomaly

TECHNICAL MEMORANDUM

INTERPLANETARY MISSION DESIGN HANDBOOK: EARTH-TO-MARS MISSION OPPORTUNITIES AND MARS-TO-EARTH RETURN OPPORTUNITIES 2009–2024

INTRODUCTION

This document provides trajectory designers and mission planners information about Earth-Mars and Mars-Earth trajectory opportunities for the years 2009 to 2024. These studies were performed in support of a human Mars mission scenario described below. All of the trajectories and "porkchop plots" in appendix A were developed using the Mission Analysis Environment (MAnE) software tool for heliocentric high-thrust missions and its optimization module Heliocentric Interplanetary High-Thrust Trajectory Optimization Program (HIHTOP). These plots show departure energies, departure speeds, and declinations, along with arrival speeds and declinations for each opportunity.

The plots provided here are intended to be more directly applicable for the human Mars mission than general plots available in other references. In addition, a summary of optimal cargo and piloted mission trajectories are included for each opportunity. Also, a number of additional studies were performed. These included determining the effect of thrust-to-weight (T/W) ratios on gravity losses, total time-of-flight (TOF) tradeoffs for the 2014 piloted opportunity, all-chemical propulsion systems, and crew radiation time exposure. Appendix B provides free-return trajectories in case of an abort on an outbound trip.

HUMAN MARS DESIGN REFERENCE MISSION OVERVIEW

The design reference mission (DRM) is currently envisioned to consist of three trans-Mars injection (TMI)/flights: two cargo missions in 2011, followed by a piloted mission in 2014. The cargo missions will be on slow (near Hohmann-transfer) trajectories with an in-flight time of 193–383 days. The crew will be on higher energy, faster trajectories lasting no longer than 180 days each way in order to limit the crew's exposure to radiation and other hazards. Their time spent on the surface of Mars will be approximately 535–651 days (figure 1). A summary of the primary cargo and piloted trajectories is summarized in table 1.

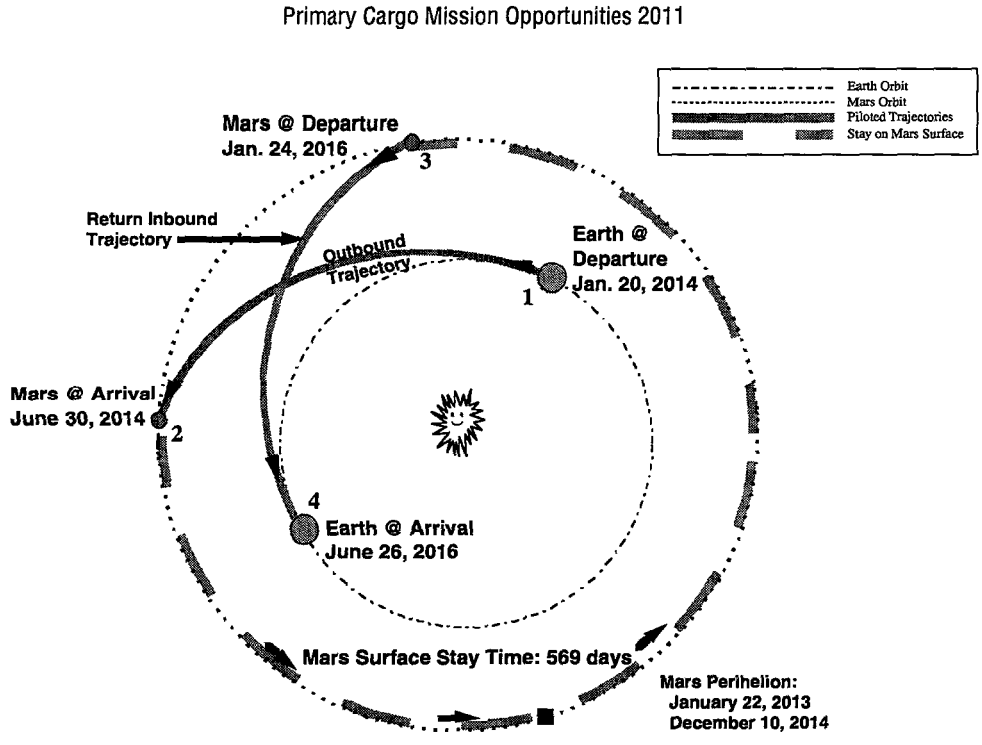


Figure 1. 2014 primary piloted opportunity.

Figure 2 shows an overview of the DRM opportunity and figure 3 shows the DRM architecture. Each payload component will be delivered to orbit by a launch vehicle capable of lifting 80 mt into low-Earth orbit (LEO) in two phases, 30 days apart, and approximately 1 month before the expected departure date. Each mission will be initially assembled in LEO at an altitude of approximately 400 km (inclination ~ 28.5°), from where the TMI burn will be performed to initiate the transfer to Mars. In order to minimize the effect of velocity losses, two periapse burns will be performed at departure. The TMI propulsion system will be a nuclear thermal propulsion system consisting of three engines capable of producing 15,000 lb of thrust (lb_f), each (with effective specific impulse (I_{sp}) of 931 sec).

Table 1. DRM baseline cargo and piloted trajectories.

Primary Piloted Mission Opportunity 2011

Mission	Launch Date (m/d/yr)	TMI ΔV (m/sec)	Velocity Losses (m/sec)	C_3 (km^2/sec^2)	Mars Arrival Date	Transfer Time (days)
Cargo 1	11/8/11	3,673	92	8.95	8/31/12	297
Cargo 2	11/8/11	3,695	113	8.95	8/31/12	297

Primary Piloted Mission Opportunity 2014

Launch Date	TMI ΔV (m/sec)	Velocity Losses (m/sec)	C_3 (km^2/sec^2)	Outbound TOF (days)	Mars Arrival Date	Mars Stay (days)	Mars Depart Date	TEI ΔV (m/sec)	TOF (days)	Earth Arrival Date	Total TOF (days)
1/20/14	4,019	132	15.92	161	6/30/14	573	1/24/16	1,476	154	6/26/16	888
1/22/14	4,018	131	15.92	180	7/21/14	568	2/9/16	1,476	180	8/7/16	928

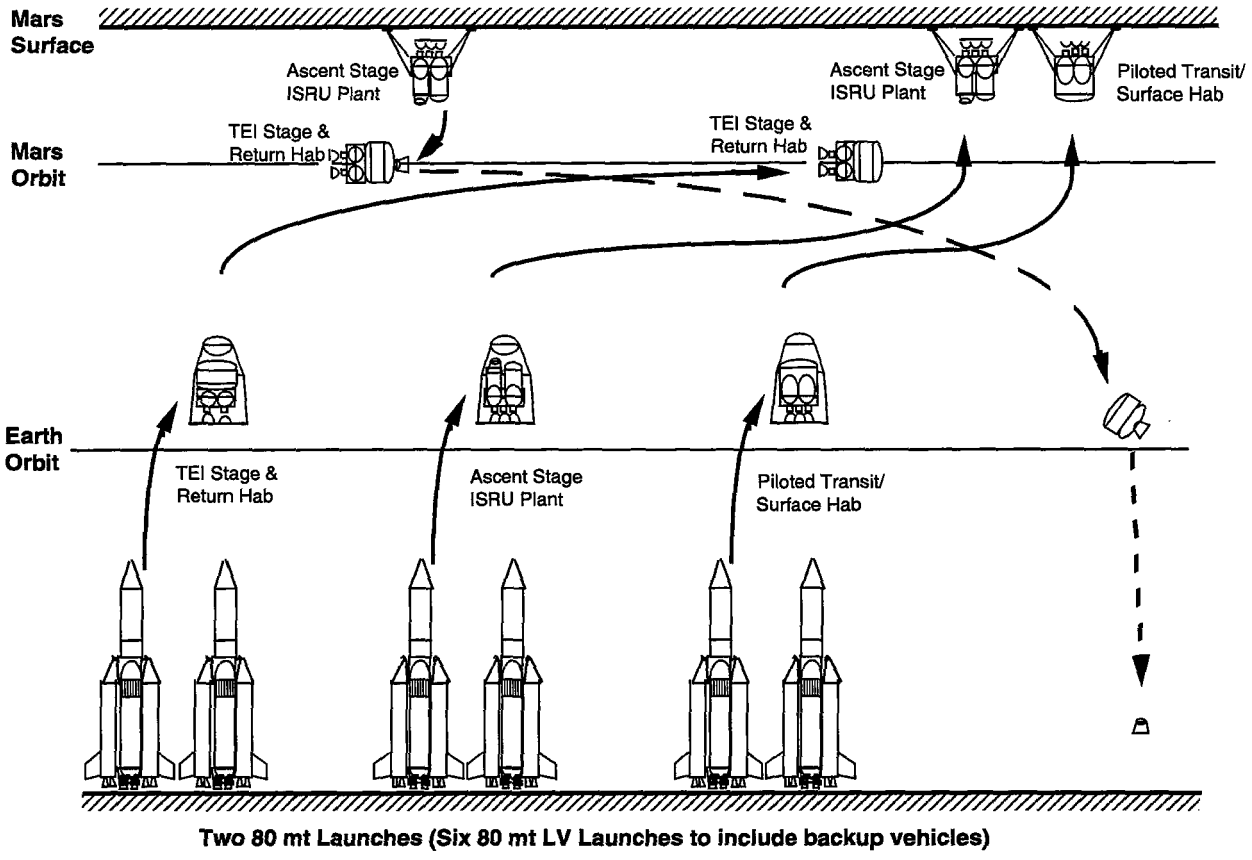
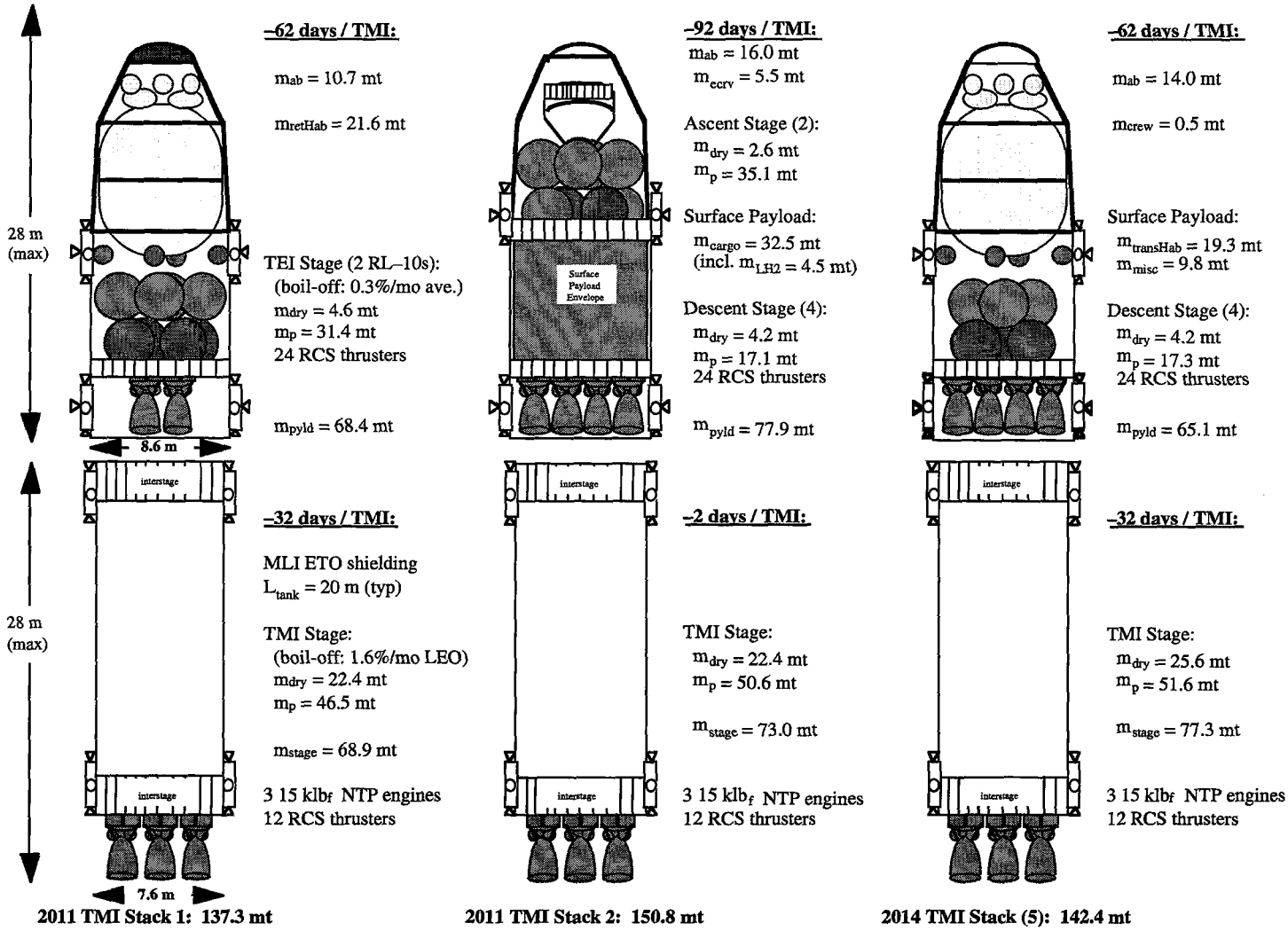


Figure 2. DRM 2014 opportunity.

Human Mars Mission: Design Reference Mission

DRM "Scrub v3.0" Architecture: 2011 / 2014 Opportunity



–62 days / TMI:

m_{ab} = 10.7 mt

m_{retHab} = 21.6 mt

TEI Stage (2 RL–10s):
(boil-off: 0.3%/mo ave.)
m_{dry} = 4.6 mt
m_p = 31.4 mt
24 RCS thrusters

m_{pyld} = 68.4 mt

–32 days / TMI:

MLI ETO shielding
L_{tank} = 20 m (typ)

TMI Stage:
(boil-off: 1.6%/mo LEO)
m_{dry} = 22.4 mt
m_p = 46.5 mt

m_{stage} = 68.9 mt

3 15 klb_f NTP engines
12 RCS thrusters

2011 TMI Stack 1: 137.3 mt

–92 days / TMI:

m_{ab} = 16.0 mt
m_{ecrv} = 5.5 mt

Ascent Stage (2):
m_{dry} = 2.6 mt
m_p = 35.1 mt

Surface Payload:
m_{cargo} = 32.5 mt
(incl. m_{LH2} = 4.5 mt)

Descent Stage (4):
m_{dry} = 4.2 mt
m_p = 17.1 mt
24 RCS thrusters

m_{pyld} = 77.9 mt

–2 days / TMI:

TMI Stage:
m_{dry} = 22.4 mt
m_p = 50.6 mt

m_{stage} = 73.0 mt

3 15 klb_f NTP engines
12 RCS thrusters

2011 TMI Stack 2: 150.8 mt

–62 days / TMI:

m_{ab} = 14.0 mt

m_{crew} = 0.5 mt

Surface Payload:
$m_{transHab}$ = 19.3 mt
m_{misc} = 9.8 mt

Descent Stage (4):
m_{dry} = 4.2 mt
m_p = 17.3 mt
24 RCS thrusters

m_{pyld} = 65.1 mt

–32 days / TMI:

TMI Stage:
m_{dry} = 25.6 mt
m_p = 51.6 mt

m_{stage} = 77.3 mt

3 15 klb_f NTP engines
12 RCS thrusters

2014 TMI Stack (5): 142.4 mt

Figure 3. DRM architecture.

The cargo 1 payload will consist of the liquid oxygen/methane (lox/CH_4) trans-Earth-injection (TEI) stage to be used for crew return, the crew's return habitat, and an aerobrake. The cargo 2 payload will consist of the empty Mars ascent stage, the lox/CH_4 production plant, the Earth crew return vehicle (ECRV), surface mobility units, the descent stage, and an aerobrake. The piloted mission payload will consist of the six-person crew, surface payload materials, a two-level surface habitat, a lox/CH_4 descent stage, and an aerobrake. Mars aerocapture will be into a 250 × 33,793 km altitude, approximately 40° inclination orbit. A restriction of 8.7 km/sec for Mars arrival entry speed (relative to Mars) was provided as the upper limit for safe entry.[1] Using equation (1),[2] it can be determined that this corresponds to an arrival V infinity (V_∞) limit of 7.167 km/sec:

$$V = \sqrt{\frac{2*\mu}{(R+h)} + V_\infty^2} \quad , \tag{1}$$

where:

μ = 42,828.3 km^3/sec^2

R = 3,397 km (Mars', radius)

h = entry altitude of 125 km (standard assumption for entry design).

The same orbit will be used by the crew for Mars departure. Upon arrival back at Earth, the ECRV will perform a near-ballistic reentry. An upper limit of 14.5 km/sec for Earth arrival speed was given as the upper limit for safe reentry.[1] Again, using equation (1), this corresponds to an arrival V_∞ limit of 9.36 km/sec where:

μ = 398,600.44 km^3/sec^2

R = 6,378.14 km (Earth's radius)

h = entry altitude of 125 km.

A more detailed list of assumptions used to develop these trajectories may be found in appendix C.

GENERAL TRAJECTORY CHARACTERISTICS

Before determining the optimal trajectories for each cargo and piloted flight, general trajectory information needs to be developed and understood for each mission opportunity. This process began with the development of "porkchop" plots for each mission opportunity. The MAnE software tool was used to compute a large number of trajectories. The (departure energies) C_3s from these trajectories were then plotted along with other mission data for ranges of Earth departure/Mars arrival and Mars departure/Earth arrival dates. This information was then used to choose the departure and arrival dates from which the MAnE module HIHTOP could optimize to a particular solution. For more information on MAnE, see appendix D.

The mission spaces in appendix A represent this trajectory performance information. Plots showing departure excess velocity, departure energy, departure declination, arrival energy, and arrival declination were developed for each opportunity. Each plot includes departure and arrival dates given in both Julian and Gregorian dates. Most of the plots also include diagonal time-of-flight (TOF) lines. The plots are also clearly marked with the most applicable mission opportunity type—cargo or piloted—given the baseline mission and assumptions described above.

Two classes of missions are normally used to described Earth-Mars transfers. In order to minimize the energy required for the transfer, it is desirable for the Earth at launch and the target planet at arrival to be nearly in direct opposition (Hohmann transfer). These are conjunction class missions, and for Earth/Mars, the launch opportunities, or synodic periods, for these transfers occur every 780 days (2.14 years). Opposition transfers are those where Mars and Earth are closest (i.e., on the same side of the Sun). They can often be very short in duration, but at a tradeoff of much more energy.[3] For these studies, only conjunction class missions were investigated.

During the early planning stages, the departure C_3 plots are the most valuable to determine optimal mission opportunities.[2] Figure 4 shows the C_3 "porkchop plot" for the primary 2014 conjunction class opportunities.

The two separate areas on the plots can be distinguished as type I and type II trajectories. If the spacecraft travels less than a 180° true anomaly, the trajectory is termed type I. If the spacecraft travels more than 180° and less than 360°, then it is a type II transfer.[4] Generally, the cargo missions are type II trajectories and the piloted missions are type I trajectories (the exceptions are the cargo missions in 2018 and 2020, discussed later). Note that these plots also experience a dramatic rise along a "ridge" passing diagonally from lower left to upper right across the mission space. This disturbance is associated with all near-180° transfer trajectories. In three-dimensional space, the fact that all planetary orbits are not strictly coplanar causes such transfer arcs to require high ecliptic inclinations. This condition culminates in a polar flight path for an exact 180° ecliptic longitude increment between departure and arrival points and an associated very large energy requirement for transfers. In MAnE, "solutions to Lambert's problem are typically less accurate in the vicinity of transfers that are multiples of 180°" and will tend to

have problems converging.[5] This separation between the two regions reinforced the necessity of narrowing down a target region for the desired transfer before attempting to begin optimization to a specific trajectory.

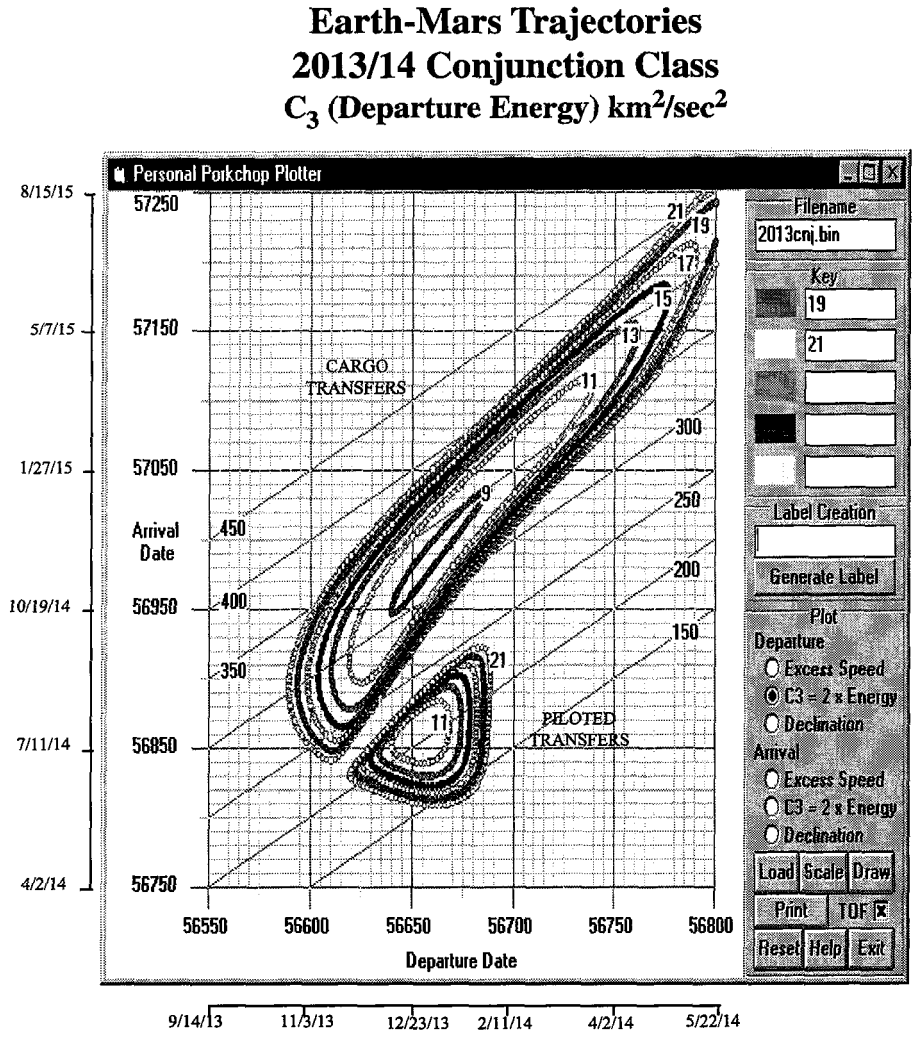


Figure 4. C_3 departure energies for 2014 opportunities.

For the cargo missions, these plots may be used to determine the minimum initial energy needed to achieve departure (good indicator of initial mass in LEO and hence mission cost). On the other hand, for the piloted missions they may be used to determine the minimum excess velocity achievable for a certain TOF (180 days, for example). For example, since for both the outbound and return flights the only maneuver is performed at departure, one would expect the minimum initial mass for the maneuver to fall somewhere in the minimum C_3 area. Note there are two minimum energy areas—one associated with type I transfers and one associated with type II transfers. In order to converge on an optimal cargo solution, HIHTOP would need to be initiated in the type II vicinity near a minimum initial energy.

The preferred choice of the two solutions depends on the circumstances. For example, for the 2014 cargo missions in figure 4, the optimal condition would be in the center of the 3 km/sec departure velocity. In this case, a departure date (modified Julian date) of 56660 with a transfer time of 325 days was used as a starting point to find the lowest initial mass in LEO. On the other hand, for the piloted mission, a 180-day transfer would require a higher departure speed (around 3.4 km/sec). In this case a starting point of 56660 with an end condition specified of 180 days in flight was used as the starting point for optimization.

Occasionally, arrival speeds at Mars and Earth were too large to allow for safe aerobraking or reentry. In these circumstances, the Mars arrival excess velocity or Earth arrival excess velocity plots were examined for launch and arrival dates that met constraints. The departure and arrival dates could be modified appropriately while specifying the upper limit of the allowable entry velocity as a MAnE end condition.

It is envisioned that the declination plots will not be used until much later in the design process, but they are included here for completeness. If there is a limit or desired declination determined during later planning phases, the contour plots can provide information on available launch and arrival dates to meet those constraints.

MISSION OPPORTUNITIES

The process described above was repeated for each set of cargo and piloted opportunities for 2009–2024. Figure 5 provides a summary of the departure energies required for each optimal cargo mission. Figure 6 provides a summary of the mission times required for each optimal cargo mission opportunity.

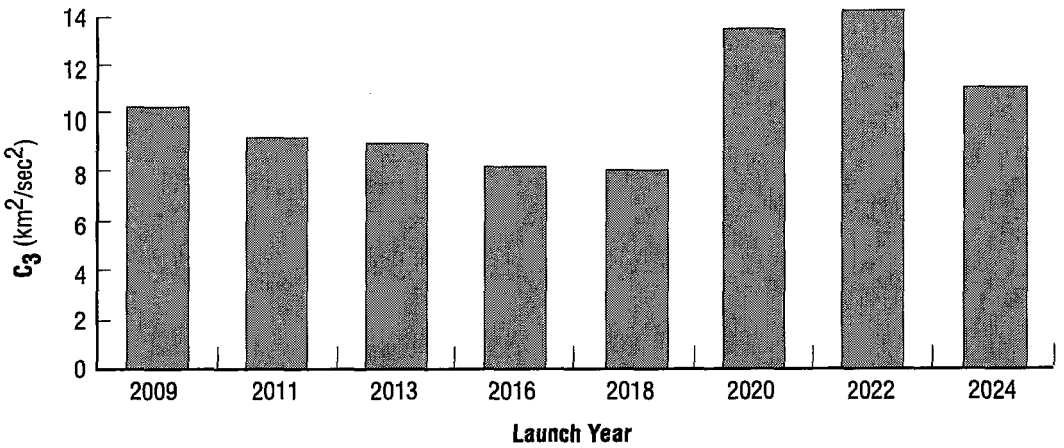


Figure 5. Cargo mission departure energies, 2009–2024.

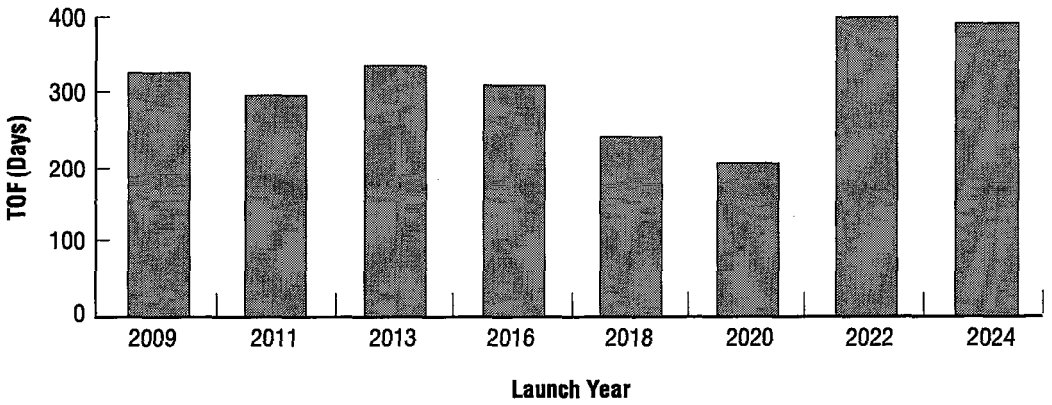


Figure 6. Cargo mission durations, 2009–2024.

Table 2 summarizes the data for the 2009–2024 cargo missions. The rapid increase in departure energy required for the 2020 cargo opportunity was unexpected. However, notice from the C_3 porkchop plot in appendix A the minimum energy transfer in this case is a type I transfer—hence the higher energy and shorter mission duration. The 2018 opportunity is also type I. However, the higher energy transfer may be due to the fact that the type II arrival would coincide very closely with the Mars aphelion date of August 3, 2020. It would thus be more efficient, relatively speaking, to reach Mars before that date, hence the type I transfer.

Table 2. Data for cargo missions, 2009–2024.

Year	C_3 (km^2/sec^2)	Transfer Time (days)	Mars Arrival Excess Entry Velocity (km/sec)	Transfer Type
2009	10.27	327	3.20	II
2011	8.95	297	2.99	II
2013	8.78	328	2.96	II
2016	7.99	305	2.83	II
2018	7.74	236	2.78	I
2020	13.17	193	3.63	I
2022	13.79	383	3.71	II
2024	11.19	345	3.35	II

Variations in C_3s can be due to many causes: the relative positions of the planets, the plane change required into the transfer orbit, the velocities of the planets, and the eccentricities of the orbits.[4] However, this relies on the superposition of two synodic variations. The first synodic period occurs every 2.14 years, or 25.6 months, and refers to the angular positions of the two planets. The second is due to the eccentricity of Mars orbit ($e = 0.093$). The planets nearly return to their original relative heliocentric position every 7–8 oppositions, or every 15–17 years.[6] The same departure energy data were plotted for the 1990–2005 opportunities in figure 7 and are listed in table 3. The effect of this 15–17 year cycle can be clearly seen in figures 5, 7, and 8. For the cargo-type missions, this cycle (highest energy trajectory) begins in 2005 and ends 17 years later, in 2022. Also note during each cycle one of the best trajectories will be a type I, shorter mission duration (2002 and 2018).

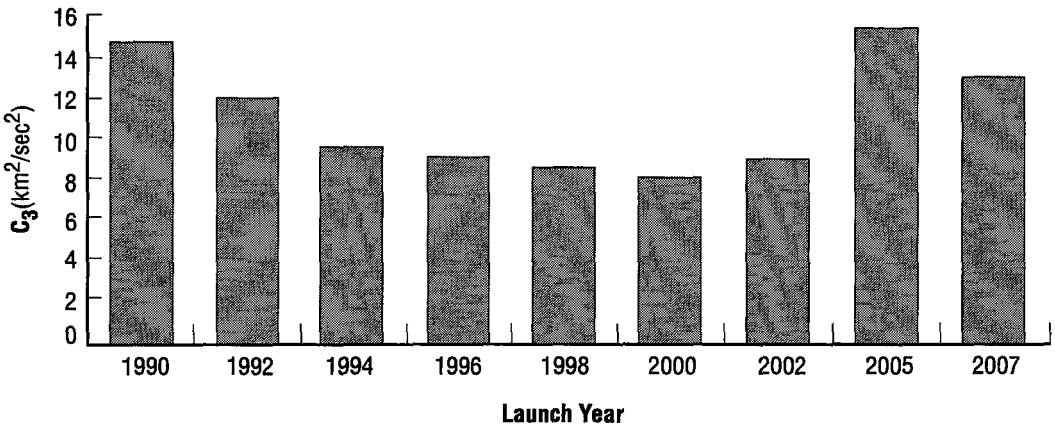


Figure 7. Cargo mission departure energies, 1990–2007.

Table 3. Data for cargo missions, 1990–2007.[7]

Year	C_3 (km^2/s^2)	Transfer Type
1990	14.39	II
1992	11.73	II
1994	9.47	II
1996	8.93	II
1998	8.44	II
2000	7.85	II
2002	8.81	I
2005	15.45	II
2007	12.75	II

Figure 8 shows the piloted departure C_3s for minimum initial departure mass in LEO for 180-day outbound mission flights. Table 4 summarizes the data for these missions. The return trips were optimized based on lowest initial mass required in Mars departure orbit.

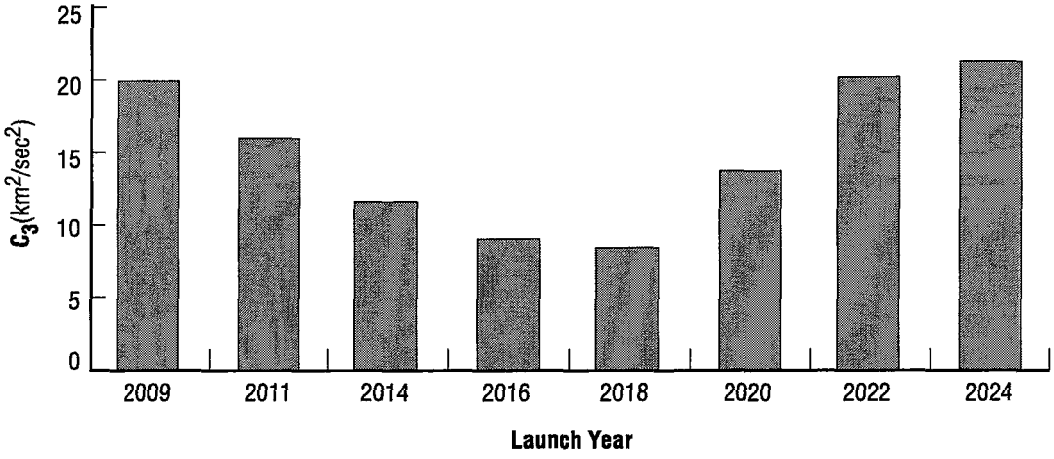


Figure 8. Piloted optimal departure energies, 2009–2024.

Table 4. Data for optimal piloted missions.

Year	C_3 (km^2/sec^2)	Earth Departure Excess Entry Velocity (km/sec)	Mars Arrival Excess Entry Velocity (km/sec)	Earth Arrival Excess Entry Velocity (km/sec)	Earth Arrival Entry Speed (km/sec)
*2009	20.06	6.51	8.17	9.35**	14.49**
*2011	15.92	7.07	8.62	9.31	14.47
2014	11.04	6.79	8.39	7.34	13.29
2016	8.87	5.30	7.24	4.01	11.78
2018	8.11	3.26	5.91	3.50	11.61
2020	13.43	3.15	5.86	5.28	12.27
*2022	19.63	4.62	6.76	7.62	13.44
*2024	20.85	6.09	7.84	9.25	14.43

* Baseline trajectory.

** At the true minimum ΔV of 4,065 km/sec, the excess entry velocity at Earth is 9.56 km/sec (exceeds limit of 9.36 km/sec).

Notice that the 2011 opportunity departure energy encompasses the departure energy required for subsequent mission opportunities through 2020. This fact was used to minimize the trip times (risk to human life). Therefore, for the 2014–2020 piloted missions it was assumed the 2011 mission architecture would be available—hence the in-flight times can be significantly reduced by designing to the 2011 departure energies. Table 5 provides a summary of these reduced mission duration times for the 2014–2020 piloted missions. The return mission 2011 departure excess velocities were also used to design the return legs and encompass the opportunities through 2018. The windows were determined by finding the latest possible launch opportunity at the 2011 C_3s that corresponds to a 180-day transfer leg for each of the outbound and return missions. See appendix A for a complete summary of opportunities for each year.

Table 5. Baseline piloted mission durations, 2014–2020.

Year	Mission Duration (days)	Mars Arrival Excess Entry Velocity (km/sec)	Earth Arrival Excess Entry Velocity (km/sec)	Departure Window (days)	Return Window (days)
*2014	161**	7.17	8.91	3	17
*2016	137**	7.17	8.91	8	30
*2018	115	6.85	4.38	27	10
*2020	151	4.27	5.28	12	1

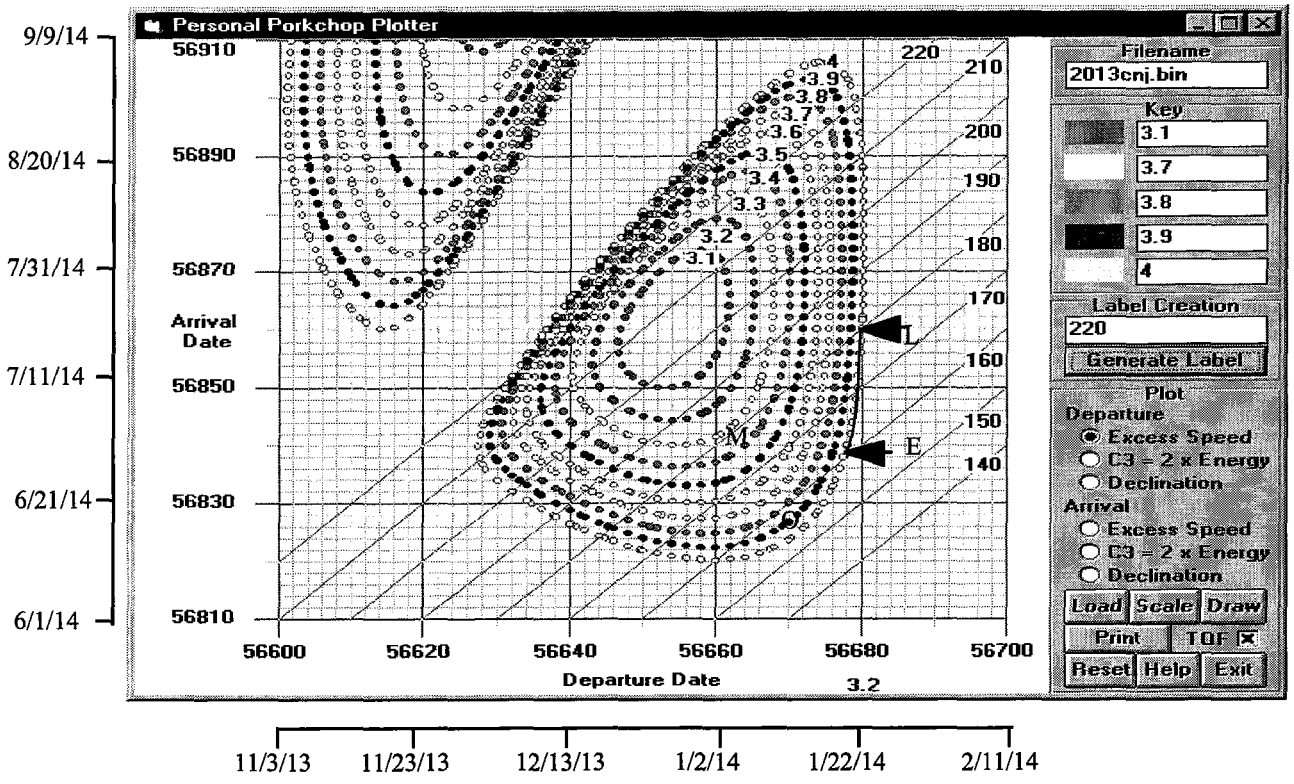
* Baseline trajectory.
**Entry velocity requirement at Mars exceeded for shorter flight times.

Figure 9 provides a detailed mapping of the 2014 piloted mission opportunity. One can easily identify the optimal transfer, the optimal transfer at the 2011 departure C_3, the baseline trajectory that meets aerobrake criterion, and the latest possible launch at a TOF of 180 days.

For the piloted missions, the baseline missions are those from tables 4 and 5 indicated with a single asterisk. The 2009 departure energy was not chosen as the baseline minimum because it was decided that the probability of a manned Mars mission capability that early would be very slim. By choosing the 2011 architecture, the maximum amount of potential missions could be enveloped.

Table 6 lists all of the baseline trajectories for each mission opportunity. Note the ΔVs in table 6 include velocity losses and assume two burns at Earth departure. A more comprehensive listing of opportunities may be found in appendix A. Although these were generated using the DRM assumptions, they should be applicable for any Earth/Mars mission using similar TMI and TEI propulsion systems (I_{sp} and T/W ratios), entry assumptions, and payload delivery requirements.

Earth-Mars Trajectories
2013/14 Piloted Missions
Baseline Mission Designed to
2011 Departure Excess Speed



E=Minimum flight time trajectory using 2011 Piloted Mission Departure Excess Speed (3.99 km/sec) and while maintaining acceptable Mars entry velocity needed for aerobraking.
Departure: 1/20/14 (56678J) Arrival: 6/30/14 (56839J)

L=Latest possible trajectory to keep flight time limited to 180 days. The acceptable window of opportunity for launch will be along the arc from E to L.
Latest Departure: 1/22/14 (56679J) Arrival: 7/21/14 (56859J)

O=Minimum flight time trajectory using 2011 Piloted Mission Departure Excess Speed (3.99 km/sec). Mars arrival excess speed=8.56 km/sec, which exceeds the limit of 7.167 km/sec
Departure: 1/13/14 (56671J) Arrival: 6/16/14 (56825J)

M=Minimum departure excess speed and initial mass trajectory for 2014 opportunity for a flight time of 180 days.
Departure: 1/4/14 (56662J) Arrival:7/3/14 (56842J)

Figure 9. Design reference mission 2014 piloted opportunities.

Table 6. Summary of all cargo and piloted opportunities, 2009–2024.

Mission Type	Launch Year	Launch Date (m/d/yr)	TMI ΔV (m/sec)	Velocity Losses* (m/sec)	Mars Arrival Date (m/d/yr)	Outbound Flight Time (days)	Mars Stay Time (days)	Mars Departure Date (m/d/yr)	TEI ΔV (m/sec)	Return Time (days)	Return Date (m/d/yr)	Total Mission Duration (days)	C_3 (km^2/sec^2)	Total of Major Mission ΔVs (TMI + TEI) (m/sec)
Cargo 1	2009	10/14/09	3,737	97	9/6/10	327	—	—	—	—	—	—	10.27	3,737
Cargo 2	2009	10/14/09	3,760	120	9/6/10	327	—	—	—	—	—	—	10.27	3,760
Piloted	2009	10/30/09	4,219	153	4/28/10	180	536	10/16/11	1,780	180	4/13/12	896	20.06	5,999
Cargo 1	2011	11/8/11	3,673	92	8/31/12	297	—	—	—	—	—	—	8.95	3,673
Cargo 2	2011	11/8/11	3,695	113	8/31/12	297	—	—	—	—	—	—	8.95	3,695
Piloted	2011	12/2/11	4,019	132	5/30/12	180	538	11/19/13	1,476	180	5/18/14	898	15.92	5,495
Cargo1	2013	12/31/13	3,665	91	11/24/14	328	—	—	—	—	—	—	8.78	3,665
Cargo 2	2013	12/31/13	3,686	112	11/24/14	328	—	—	—	—	—	—	8.78	3,686
Piloted	2014	1/20/14	4,019	132	6/30/14	161	573	1/24/16	1,476	154	6/26/16	888	15.92	5,495
Cargo 1	2016	3/21/16	3,627	88	1/20/17	305	—	—	—	—	—	—	7.99	3,627
Cargo 2	2016	3/21/16	3,647	109	1/20/17	305	—	—	—	—	—	—	7.99	3,647
Piloted	2016	3/14/16	4,019	132	7/29/16	137	630	4/20/18	1,476	130	8/28/18	897	15.92	5,495
Cargo 1	2018	5/17/18	3,615	87	1/8/19	236	—	—	—	—	—	—	7.74	3,615
Cargo 2	2018	5/17/18	3,635	108	1/8/19	236	—	—	—	—	—	—	7.74	3,635
Piloted	2018	5/18/18	4,019	132	9/10/18	115	651	6/22/20	1476	158	11/27/20	924	15.92	5,333
Cargo 1	2020	7/18/20	3,877	109	1/27/21	193	—	—	—	—	—	—	13.17	3,877
Cargo 2	2020	7/18/20	3,903	135	1/27/21	193	—	—	—	—	—	—	13.17	3,903
Piloted	2020	7/24/20	4,019	132	12/22/20	151	586	7/31/22	1,706	180	1/27/23	917	15.92	5,725
Cargo 1	2022	9/14/22	3,906	112	10/2/23	383	—	—	—	—	—	—	13.79	3,906
Cargo 2	2022	9/14/22	3,933	138	10/2/23	383	—	—	—	—	—	—	13.79	3,933
Piloted	2022	9/10/22	4,198	152	3/9/23	180	543	9/2/24	1,860	180	3/1/25	903	19.63	6,058
Cargo 1	2024	10/5/24	3,782	101	9/15/25	345	—	—	—	—	—	—	11.19	3,782
Cargo 2	2024	10/5/24	3,805	124	9/15/25	345	—	—	—	—	—	—	11.19	3,805
Piloted	2024	10/17/24	4,257	158	4/15/25	180	535	10/2/26	1,841	180	3/31/27	895	20.85	6,098

* Based on two departure perigee burns at Earth departure

ADDITIONAL STUDIES AND APPENDIX INFORMATION

Total Time of Flight Trade Studies—2014 Opportunity

In addition to developing the "porkchop" plots and determining the optimal trajectories for each mission opportunity, a few additional side studies were performed. These included TOF trade studies for the 2014 piloted mission, T/W effects on velocity losses, all-chemical propulsion systems, and determining how much time would be spent in Earth's radiation belts.

First, TOF trades studies were looked at for the primary 2014 piloted mission. The duration of the outbound and return legs was varied to determine the effect on total mission cost (initial masses of cargo 1 and piloted outbound flights in LEO). The results of this study are displayed in figure 10. The maximum benefit results from lengthening the total TOF to 360 days and choosing an outbound flight time to 173 days and return flight time to 187 days. The uneven tradeoff results from the fact that the cargo 1 mission carries the TEI stage, so the benefit from lengthening the return flight is greater than the benefit of lengthening the outbound flight. A more thorough discussion and listing of the data may be found in appendix E.

PLOT DATA:

TOF outbnd (days)	TOF inbnd (days)	Total TOF (days)	Total Initial Mass (mt)
161	154	315	276.67
161	160	321	273.99
161	170	331	270.61
171	160	331	271.17
165	175	340	267.99
170	170	340	268.14
175	165	340	269.01
161	180	341	268.04
161	190	351	266.07
161	199	360	264.70
175	185	360	263.81
180	180	360	264.36
185	175	360	265.14
163	197	360	264.35
165	195	360	263.98
167	193	360	263.78
169	191	360	263.60
171	189	360	263.56
173	187	360	263.63

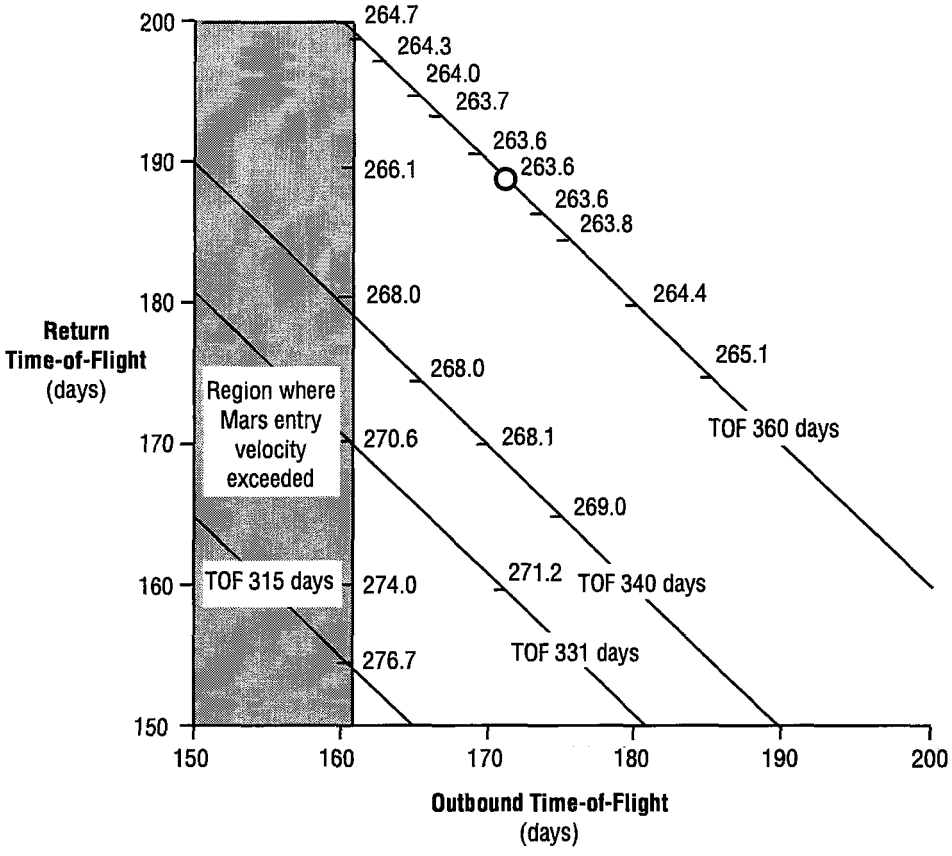


Figure 10. 2014 time-of-flight trade studies.

Velocity Losses for Various Thrust-to-Weight Ratios

In addition, the effect on velocity losses of various T/W ratios were examined. The results are displayed in figure 11. A ratio of 0.12 T/W should represent the heaviest stack envisioned for a Mars mission. The T/W ratios of 0.135, 0.143, and 0.149 were representative of the actual DRM cargo 2, piloted, and cargo 1 missions, respectively. The 0.2 T/W ratio represent the effect of adding a fourth engine to the TMI stage. In addition, single trajectories with three-burn departures with either three or four engines and two-burn departures with four engines were investigated to determine improvement in velocity losses. These results are discussed more thoroughly in appendix F.

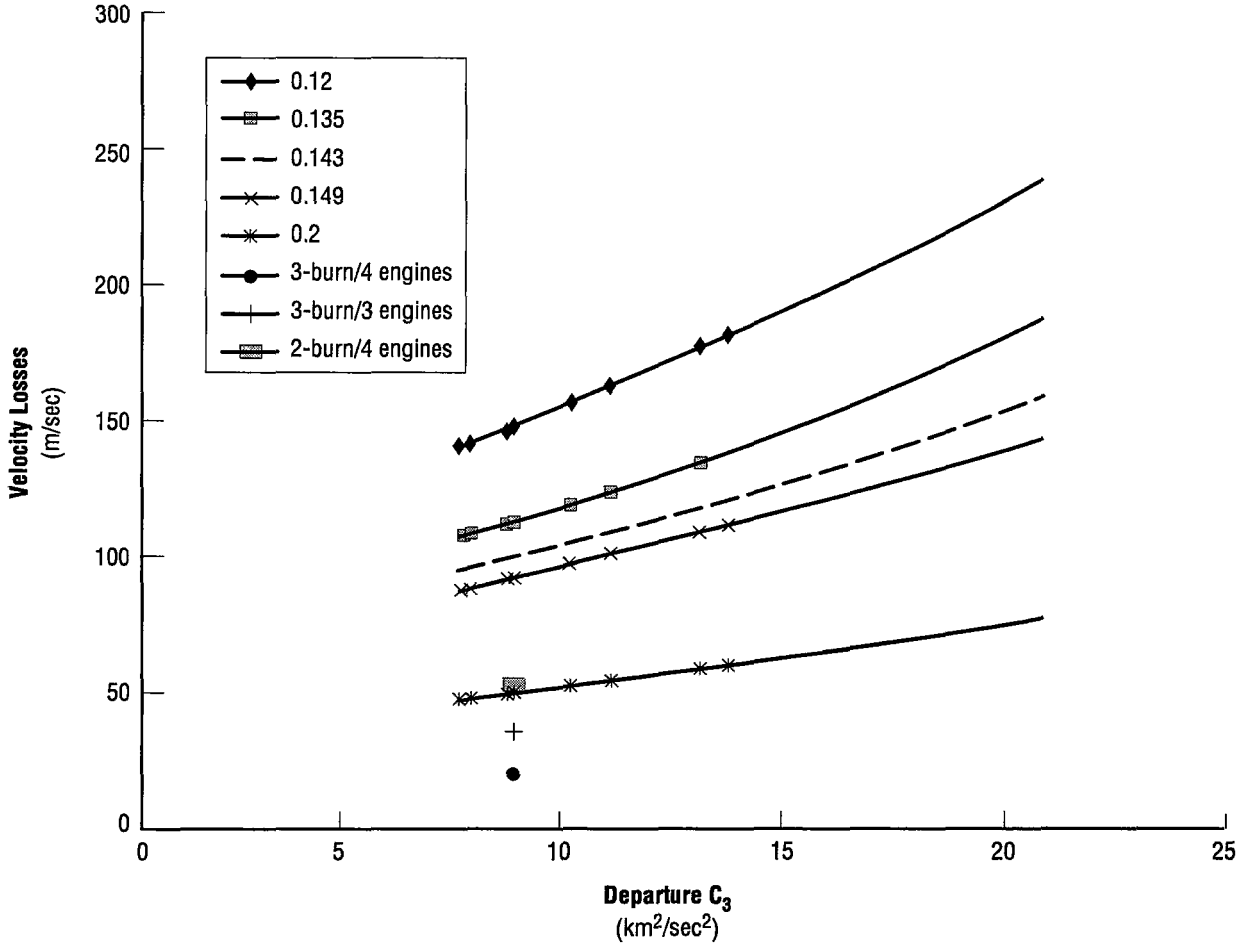


Figure 11. Velocity losses at various T/W ratios.

All-Chemical Architectures

Also briefly investigated for the primary 2011/2014 mission opportunities was the use of a chemical TMI stage (lox/LH_2). The I_{sp} was set at 480 sec, the engine weight reduced to 18.3 mt, and the thrust was increased to 100,000 lb_f. With the increased T/W ratios increased, velocity losses were reduced even though the initial mass required in LEO increased significantly due to the decreased TMI stage I_{sp}. The resultant T/W ratios, ΔVs, and velocity losses are summarized in table 7.

Table 7. All-chemical TMI transfers/DRM.

	Cargo 1		Cargo 2		Piloted	
	Baseline	Chemical	Baseline	Chemical	Baseline	Chemical
Initial Mass (mt)	135.48	187.13	150.32	208.23	140.95	191.81
Propellant Mass (mt)	44.88	100.14	50.03	111.55	50.19	108.40
% Propellant	33.1%	53.5%	24.0%	53.6%	35.6%	56.5%
T/W	0.149	0.238	0.135	0.214	0.143	0.230
ΔV Required (m/sec)	3,673	3,606	3,695	3,612	4,019	3,920
Velocity Losses (m/sec)	92.9	24.4	113.0	30.3	132.0	33.2

Time In Radiation Belts

One of the potential concerns with multiple periapse burns is the time spent in the interim orbit. Table 8 lists the required ΔVs, velocity losses, and burn times for the primary 2011 cargo 1 and 2014 piloted mission opportunities.

Table 8. ΔVs and velocity losses for two periapse burns at departure/DRM.

	ΔV_1 (km/sec)	Vel $Losses_1$ (m/sec)	Burn $Time_1$ (min)	ΔV_2 (km/sec)	Vel $Losses_2$ (m/sec)	Burn $Time_2$ (min)
Cargo 1	1.6457	29.6	17.16	2.0175	62.3	17.30
Piloted	1.7803	42.1	19.17	2.2389	90.1	19.36

First, it was assumed the proton belts began at an altitude of 1,000 km and the spacecraft would be in the region of concern at all times above this altitude. Then this is just a simple Kepler TOF problem. Using the equations from reference 4, the time in radiation belts was calculated for the cargo 1 mission and piloted missions.

First, the ideal cargo mission ΔV for the first perigee burn is 1,616.18 km/sec (1645.74–29.56). Using equation (2), the initial velocity in LEO is found to be 7.669 km/sec:

$$V_{circular} = \sqrt{\frac{\mu}{(6{,}378 + 400)}} \quad . \tag{2}$$

The velocity after performing the ΔV will be 9.2848 km/sec. Once you know this, you can find the energy $\varepsilon = -15.704$ km^2/sec^2 of the interim orbit using equation (3):

$$V_{circular} = \sqrt{2\left(\frac{\mu}{(6{,}378+400)} + \varepsilon\right)} = 9.2848 \text{ km/sec} \quad . \tag{3}$$

The semimajor axis, a, of the orbit can be calculated from equation (4) and found to be 12,691 km:

$$\varepsilon = -15.704 \text{km}^2/\text{sec}^2 = \frac{\mu}{(2a)} \quad . \tag{4}$$

From the radius of perigee (R_p = 6,778 km) and equation (5), the eccentricity, e, of the orbit is determined to be 0.4659:

$$R_p = a(1-e) \quad . \tag{5}$$

Thus, the radius of apogee R_a from equation (6) is 18,604 km, or an altitude of 12,226 km:

$$R_a = a(1+e) \quad . \tag{6}$$

The period will be 14,420 sec or 3.95 hr from equation (7):

$$\text{Period} = 2\pi\sqrt{\left(a^3/\mu\right)} . \tag{7}$$

For the piloted mission, this same procedure was followed, yielding the following orbital elements:

a = 13,684 km
e = 0.50468
Period = 4.43 hr
R_a = 20,590 km (altitude 14,212 km).

Thus, both the cargo 1 and 2 and piloted missions will spend a significant amount of time in the radiation belts during the interim coast orbit. Next, the length of time the missions will spend in the proton belts was determined. At a radius vector or 7,378 km (altitude 1,000 km), the true anomaly, ν, for the cargo mission upon entering this region can be calculated as 41.92° from equation (8):

$$R = \frac{a\left(1-e^2\right)}{1+e\cos\nu} \quad . \tag{8}$$

From this point, we will solve the Kepler TOF problem given an initial v of 41.92° and a final v of 180°. This TOF × 2 will be an approximation of the amount of time the spacecraft will spend in the radiation belt region.

Initial and final eccentric anomalies can be found to be 0.4544 rad (E_i) and π (E_f) from equation (9):

$$\cos E = \frac{e + \cos v}{1 + e \cos v} \quad . \tag{9}$$

Initial and final mean anomalies can be found to be 0.25 rad (M_i) and π (M_f) from equation (10):

$$M = E - e \sin(E) \quad . \tag{10}$$

Finally, the TOF, can be found from equation (11):

$$M_f - M_i = n \, \text{TOF} \quad , \tag{11}$$

where

$$n = \text{mean motion} = \sqrt{\left(\mu / a^3\right)} = 0.0004415 \text{ rad/sec.} \tag{12}$$

For the cargo 1 mission, this total TOF (TOF found from equation (11) ×2) was found to be equal to 3.64 hr (13,100 sec), or 92 percent of the orbit period. This is probably not much of a concern for the cargo mission. However, for the piloted mission, the TOF was 4.1 hr (14,850 sec), or 93 percent of the orbit period. Although it is expected that the majority of the radiation exposure will be during the remainder of the mission[8] (estimates around 98 percent), it will need to be considered and the crew adequately protected in a two-burn departure scenario is used.

Verification of MAnE Results

One of the first tasks undertaken in this study was to verify MAnE and the HIHTOP optimization program-provided correct results. These verifications consisted of two areas. First, previous trajectories were collected that had been generated at NASA Marshall Space Flight Center using the Swingby-Stopover Trajectory Optimization Program (SWISTO), a program that is no longer available on current platforms. SWISTO results were verified with MAnE runs to ensure departure energies, trajectories, and TOF's were comparable. In addition, plots from references 7 and 9 were generated to compare the MAnE derived results. All of these verifications were successful and are described in more detail in appendix G.

DESCRIPTION OF TRAJECTORY CHARACTERISTICS

For each year, departure C_3 and V_∞ and plots are provided for all opportunities. These are followed by enlarged views of the specific cargo and piloted mission opportunities. Note for the ecliptic projections the vernal equinox reference would be pointed to the right of the page.

Earth Departure Variables

Departure V_∞ (km/sec): Earth departure hyperbolic excess velocity. This is the difference between the velocity of the Earth with respect to the Sun and the velocity required on the transfer ellipse.

Departure C_3 (km^2/sec^2): Earth departure energy, or the square of the departure hyperbolic excess velocity (V_∞). C_3 is usually the major performance parameter required for launch vehicle sizing.

Departure declination (degrees): Earth declination of the departure V_∞ vector, may impose a launch constraint.

Mars Arrival Variables

Arrival V_∞ (km/sec): Mars centered arrival hyperbolic excess velocity, or difference between the arrival velocity on the transfer ellipse and the orbital velocity of the planet. It can be used to calculate the spacecraft velocity at any altitude, *h*, of flyby by using the equation:[9]

$$V = \sqrt{\frac{2 * \mu}{(3{,}397 + h)} + V_\infty^2} \quad , \tag{13}$$

where:

μ= 42,828.3 km^3/sec^2
Mars radius = 3,397 km
h = altitude.

Arrival declination (degrees): Mars declination of the arrival V_∞ vector.

Mars Departure Variables

Departure V_∞ (km/sec): Mars departure hyperbolic excess velocity.

Departure declination (degrees): Mars declination of the departure V_∞ vector, may impose a launch constraint.

Earth Arrival Variables

Arrival V_∞ (km/sec): Earth-centered arrival hyperbolic excess velocity. It can be used to calculate the spacecraft velocity at any altitude h of flyby by using the equation:[9]

$$V = \sqrt{\frac{2 * \mu}{(6{,}378.14 + h)} + V_\infty^2} \quad , \tag{14}$$

where:

$\mu = 398{,}600.44 \text{ km}^3/\text{sec}^2$
Earth's radius = 6,378.14 km.

Arrival declination (degrees): Earth declination of the arrival V_∞ vector.

CONCLUSIONS

In these studies, the high-thrust options for performing round-trip Mars missions were explored. Plots showing departure energies, departure speeds, and declinations, along with arrival speeds and declinations, are provided for each opportunity between 2009–2024. Trajectories that minimize initial mass required from LEO for both the cargo and piloted missions are summarized (piloted missions at 180-day TOF's). The 15- to 17-year cycle for optimal conditions for missions to Mars is clearly identifiable in both missions, resulting in optimal missions for both types in 2018. In addition, by designing to higher 2011 energies, it was determined that the piloted mission duration could be reduced by as much as 65 days in 2018. Finally, a number of additional studies were performed, and summarized, including the effect of T/W ratios on gravity losses, total TOF variations, all-chemical propulsion systems, and time spent in Earth's radiation belts.

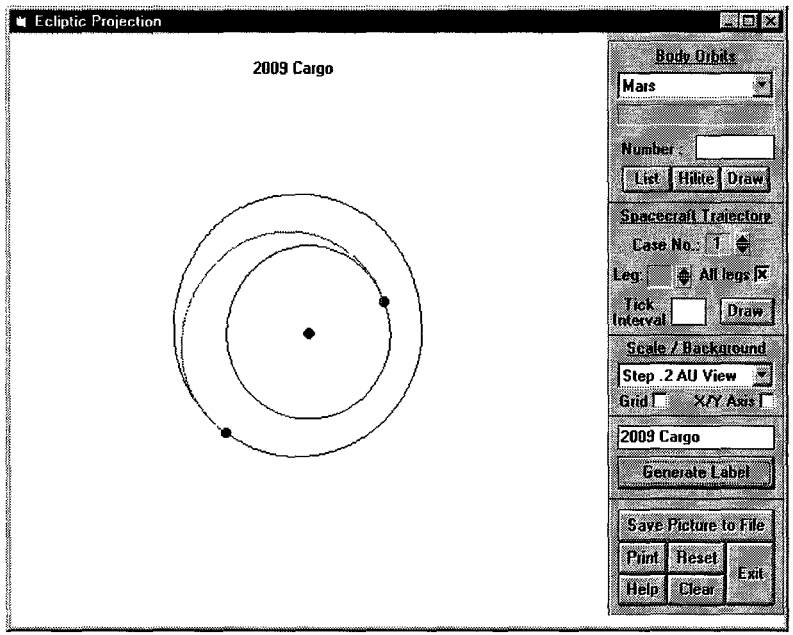
APPENDIX A—2009–2024 OPPORTUNITY PLOTS

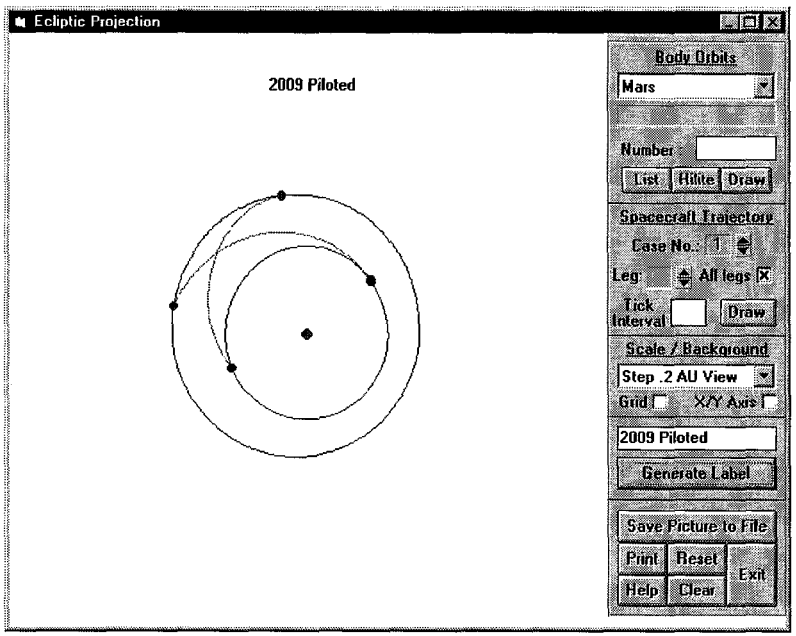
The following trajectories and "porkchop plots" were developed using the Mission Analysis Environment (MAnE) software tool for heliocentric high-thrust missions and its optimization module Heliocentric Interplanetary High-Thrust Trajectory Optimization program (HIHTOP). These plots show departure energies, departure speeds, and declinations, along with arrival speeds and declinations for each opportunity.

Table 9. 2009 opportunities summary.

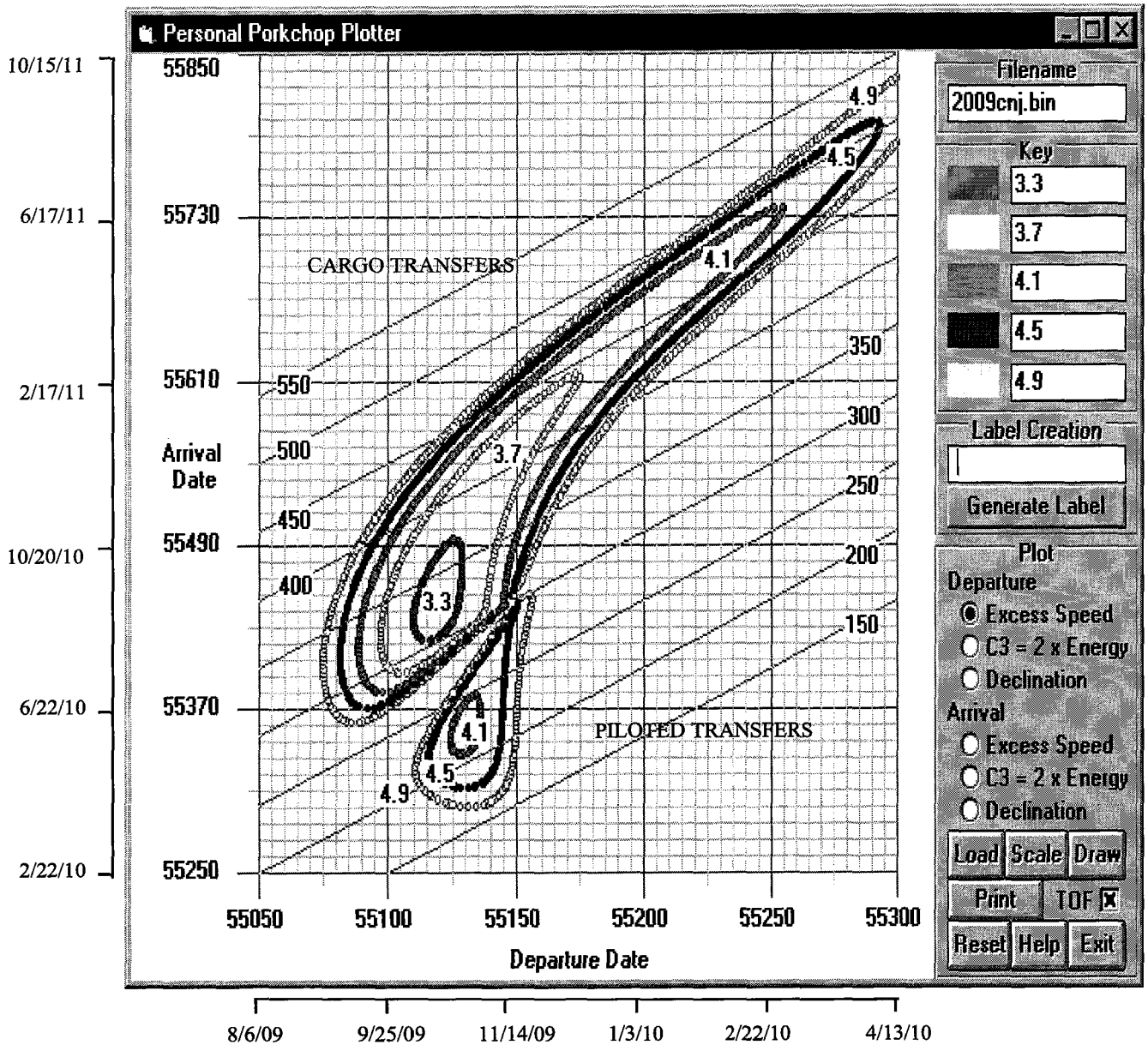
Mission Type	TMI Date (m/d/yr)	TMI ΔV (m/sec)	Velocity Losses (m/sec)	Mars Arrival Date (m/d/yr)	Outbound Flight Time (days)	Mars Stay Time (days)	Mars Departure Date (m/d/yr)	TEI ΔV (m/sec)	Return Time (days)	Return Date (m/d/yr)	Total Mission Duration (days)	C_3 (km^2/sec^2)	Total ΔV (m/sec)	Depart. V_∞ @ Earth (km/sec)	Arrival V_∞ @ Mars (km/sec)	Arrival Velocity @ Mars (km/sec)	Depart. V_∞ @ Mars (km/sec)	Arrival V_∞ @ Earth (km/sec)	Arrival Velocity @ Earth (km/sec)
Cargo 1	10/14/09	3,737	97	9/6/10	327	—	—	—	—	—	—	10.27	3,737	3.2048	2.47	5.515	—	—	—
Cargo 2	10/14/09	3,760	120	9/6/10	327	—	—	—	—	—	—	10.27	3,760	3.2048	2.47	5.515	—	—	—
Piloted *	10/30/09	4,217	152	4/28/10	180	535	10/15/11	1,778	180	4/12/12	895	20.06	5,995	4.4791	6.511	8.168	4.158	9.556	14.63
Piloted	10/30/09	4,219	153	4/28/10	180	536	10/16/11	1,780	180	4/13/12	896	20.06	5,999	4.4791	6.511	8.168	4.161	9.36	14.5

* Entry velocity limit of 14.5 km/sec at Earth exceeded

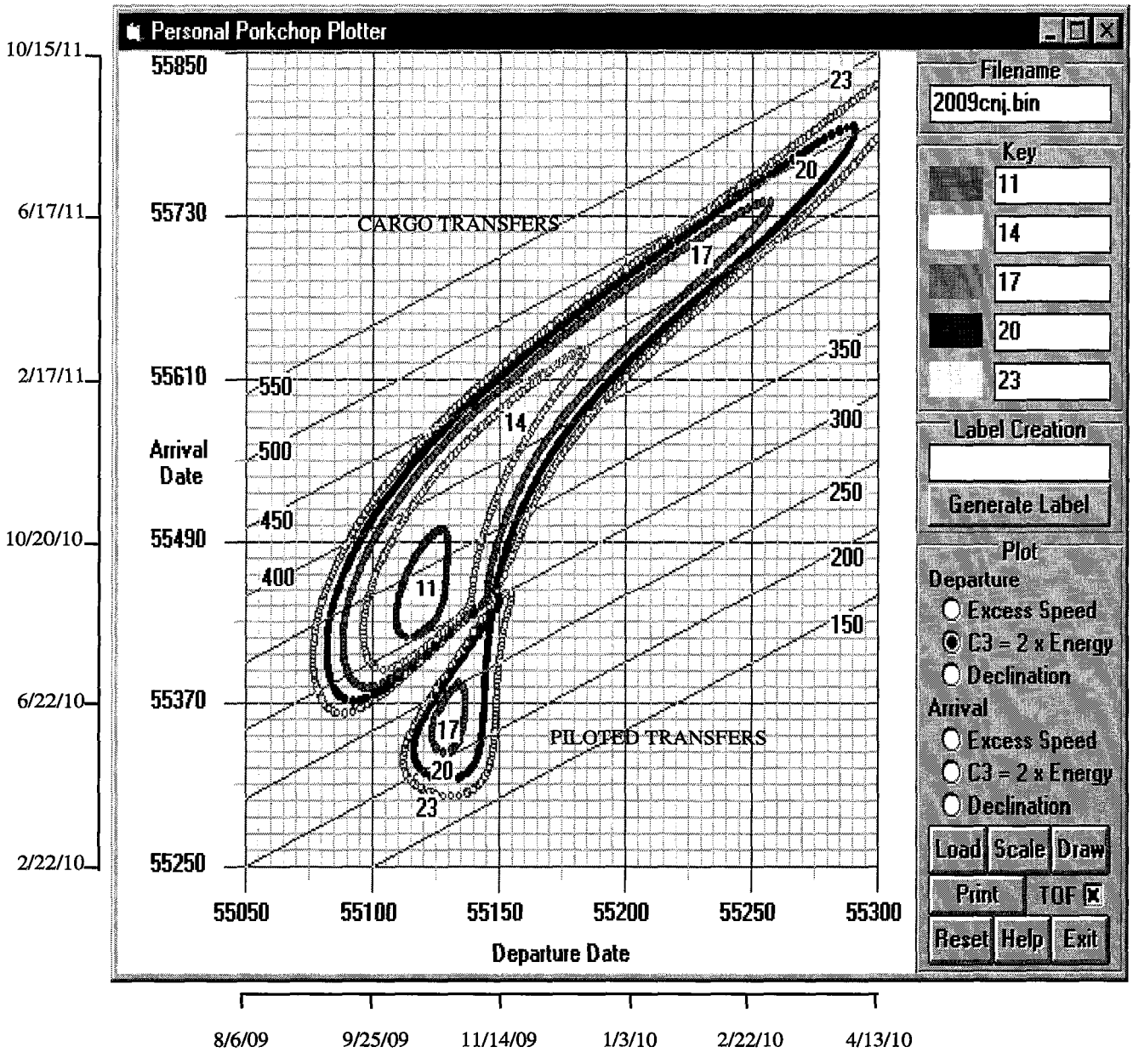




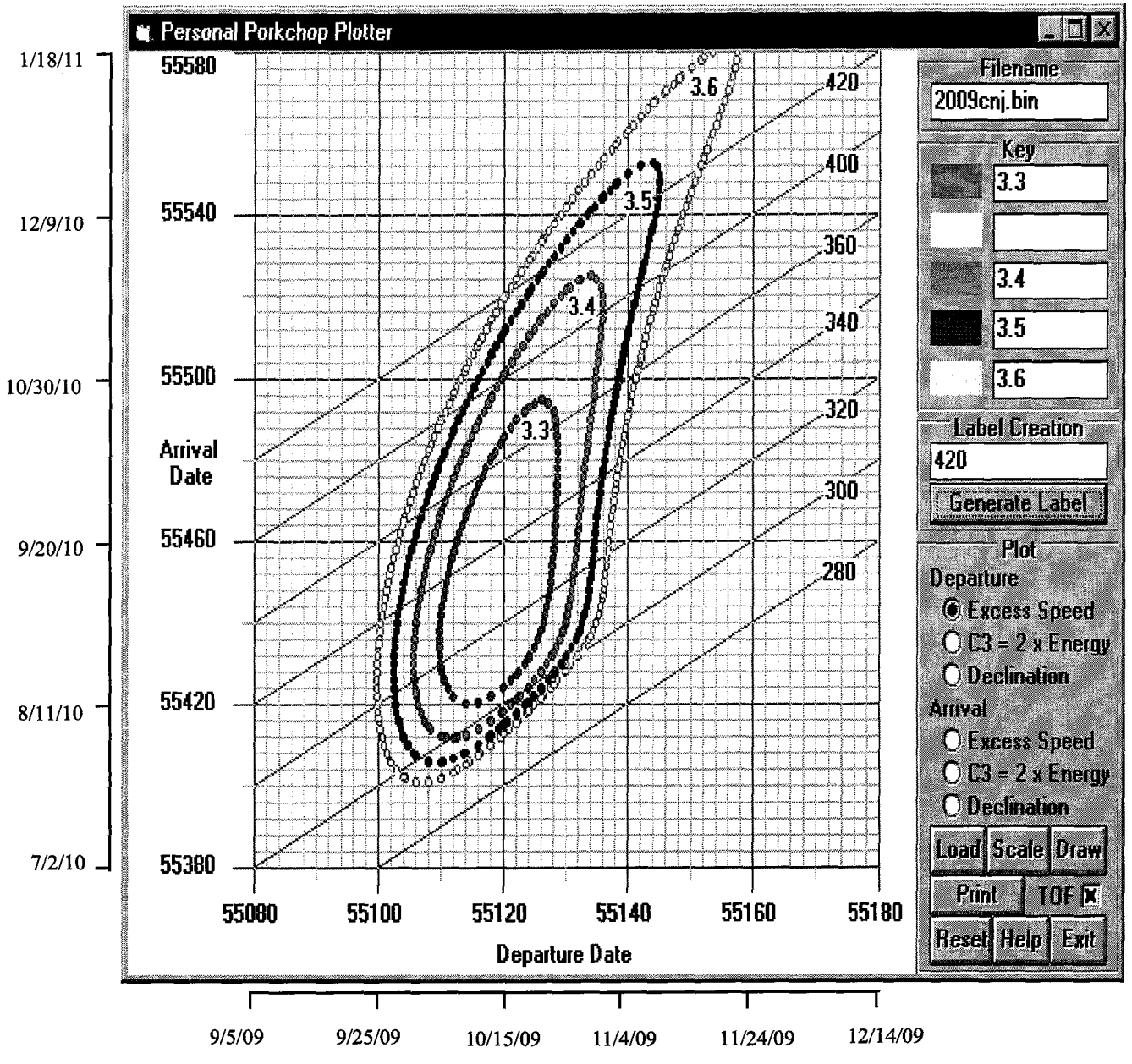
Earth-Mars Trajectories
2009 Conjunction Class
Departure Excess Speed (km/sec)



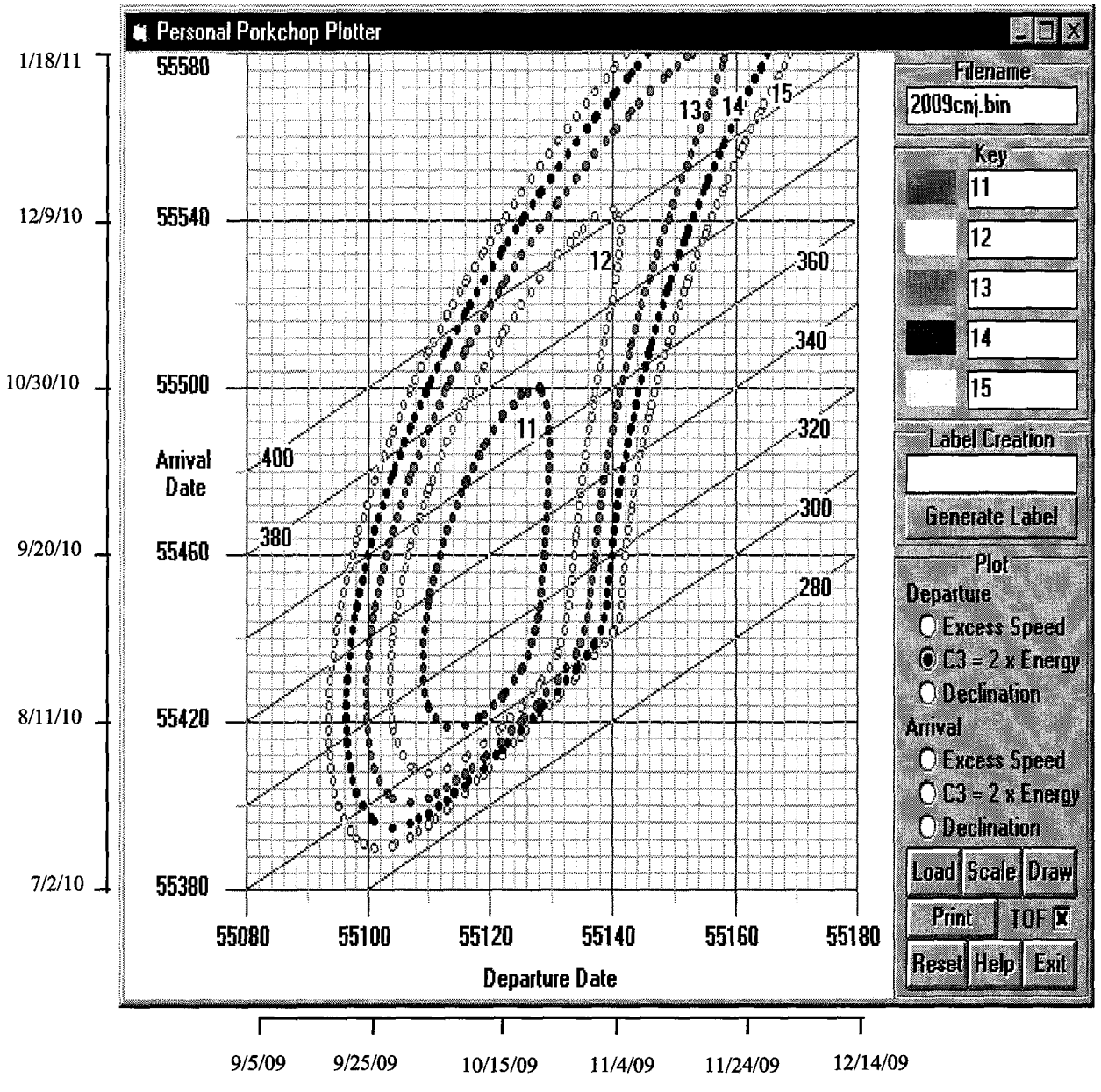
Earth-Mars Trajectories
2009 Conjunction Class
C_3 (Departure Energy) km^2/sec^2



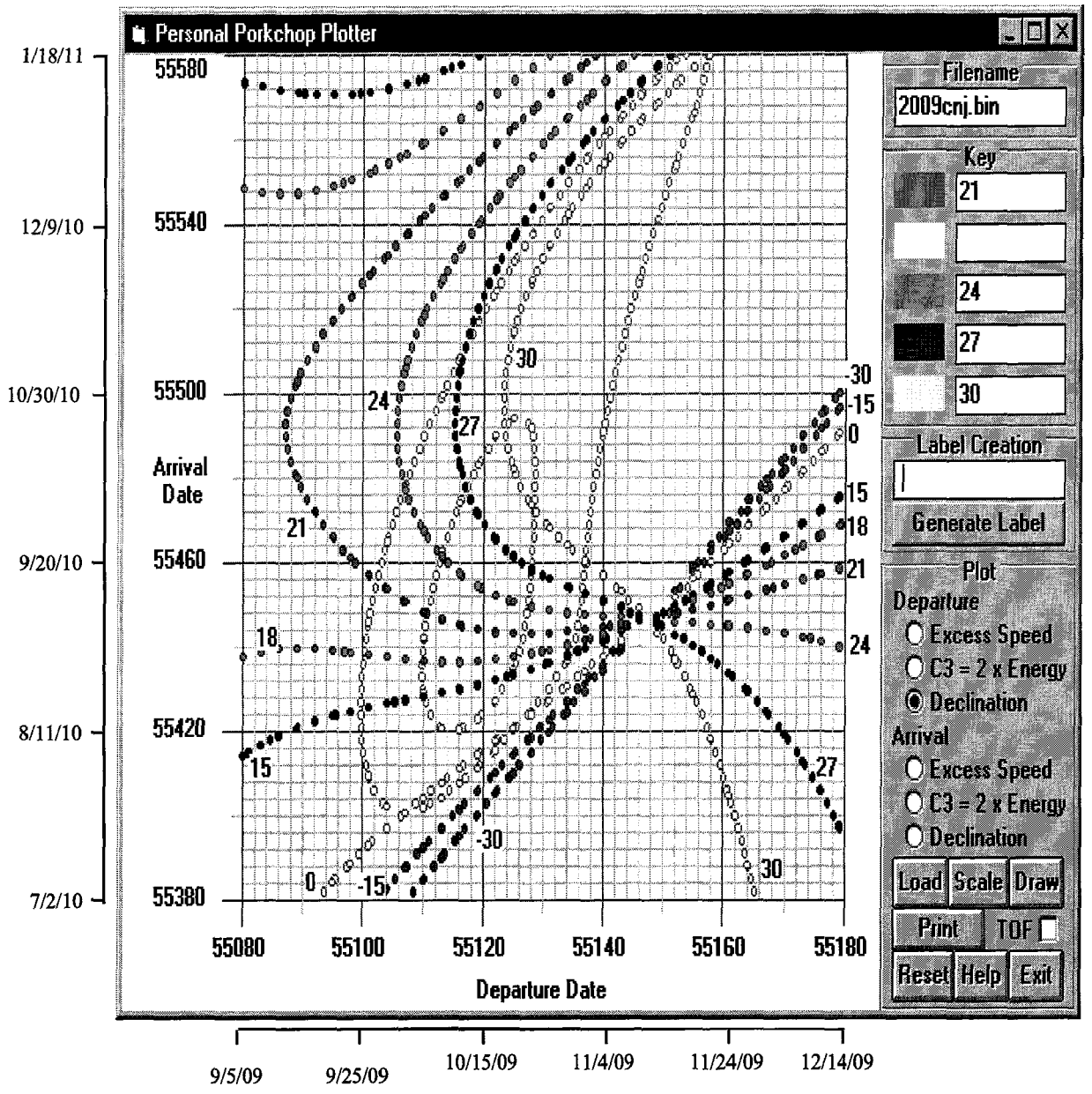
Earth-Mars Trajectories
2009 Cargo Missions
Departure Excess Speed (km/sec)



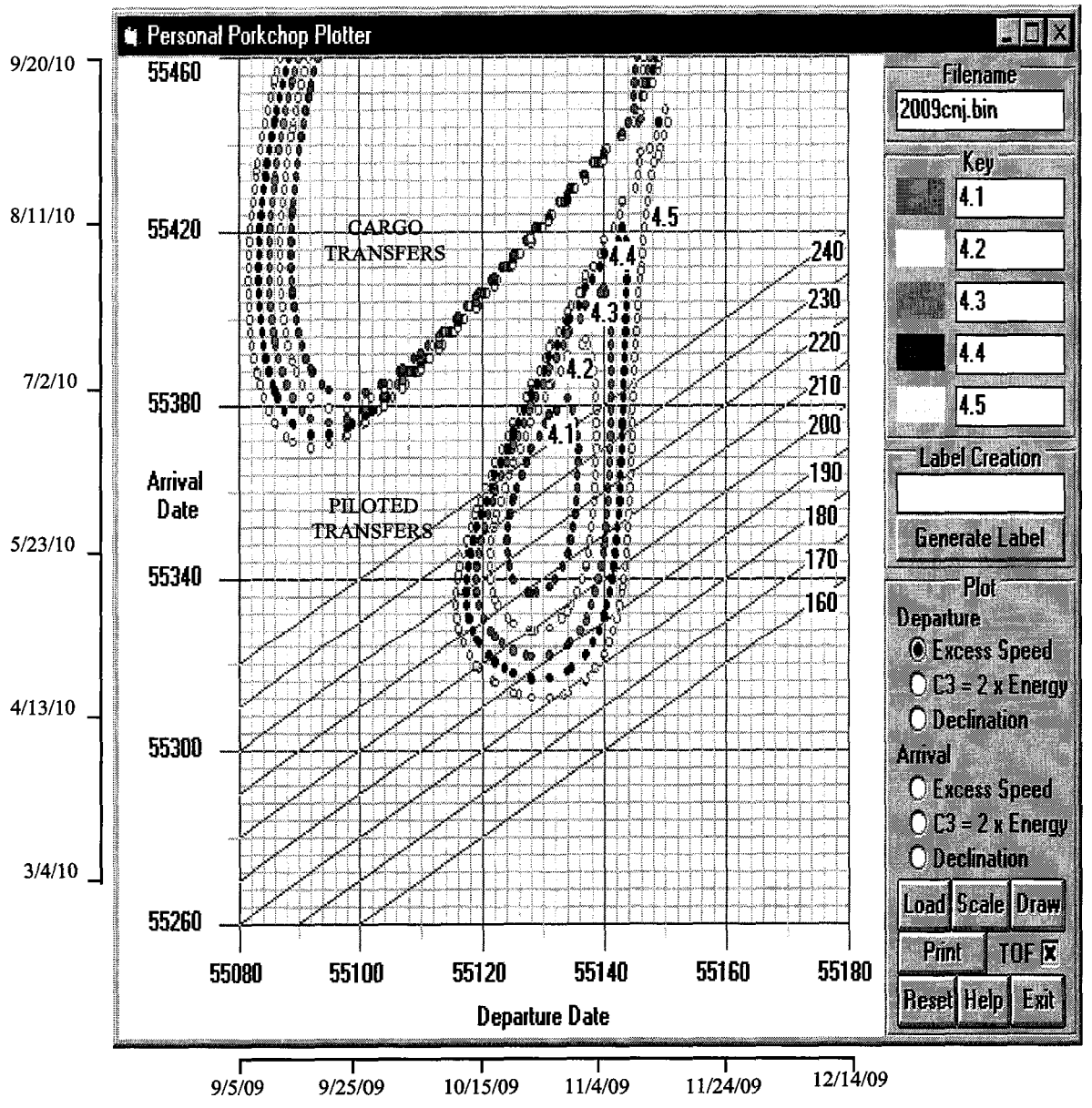
Earth-Mars Trajectories
2009 Cargo Missions
C_3 (Departure Energy) km^2/sec^2



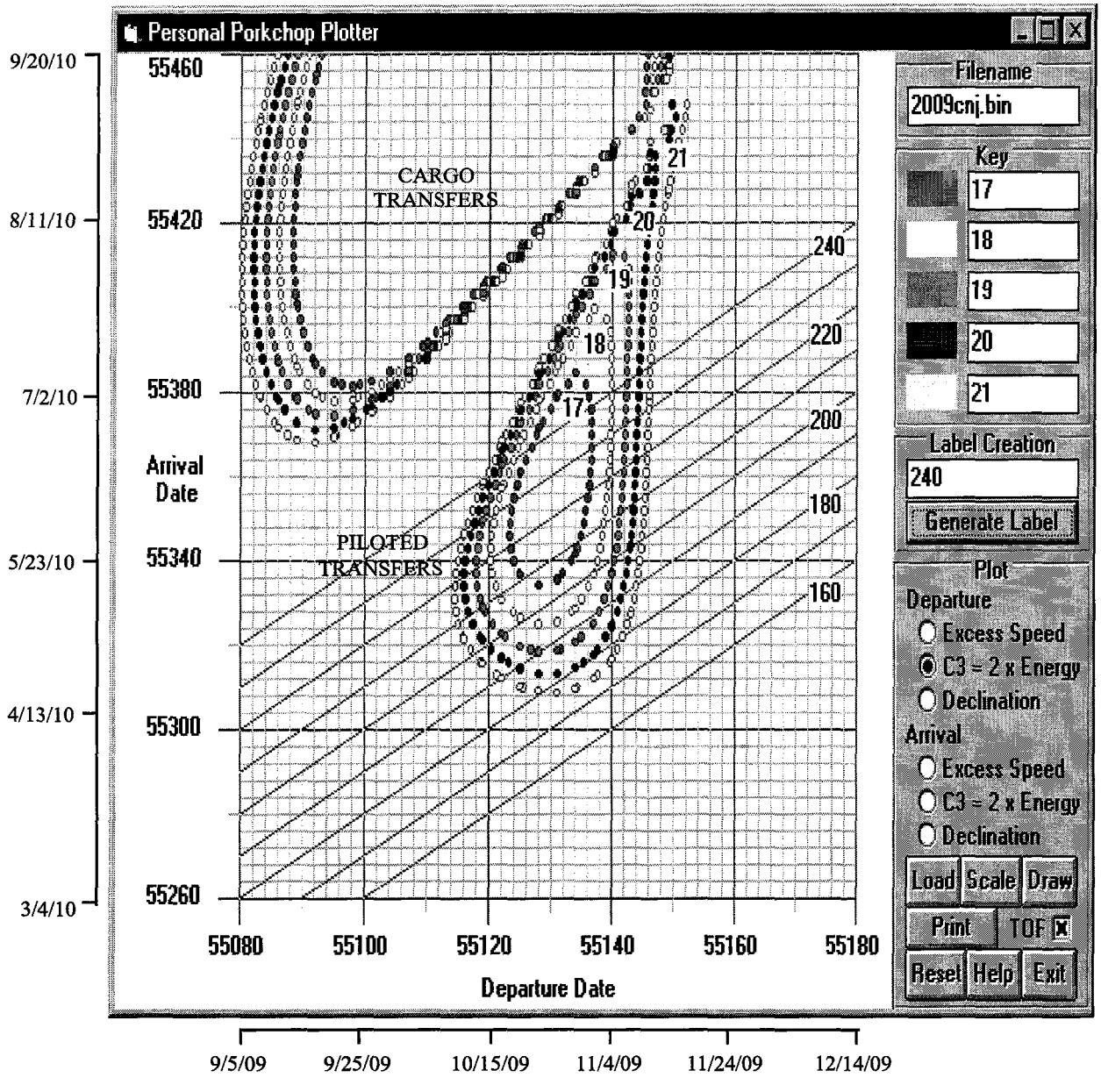
Earth-Mars Trajectories
2009 Cargo Missions
Departure Declination (Degrees)



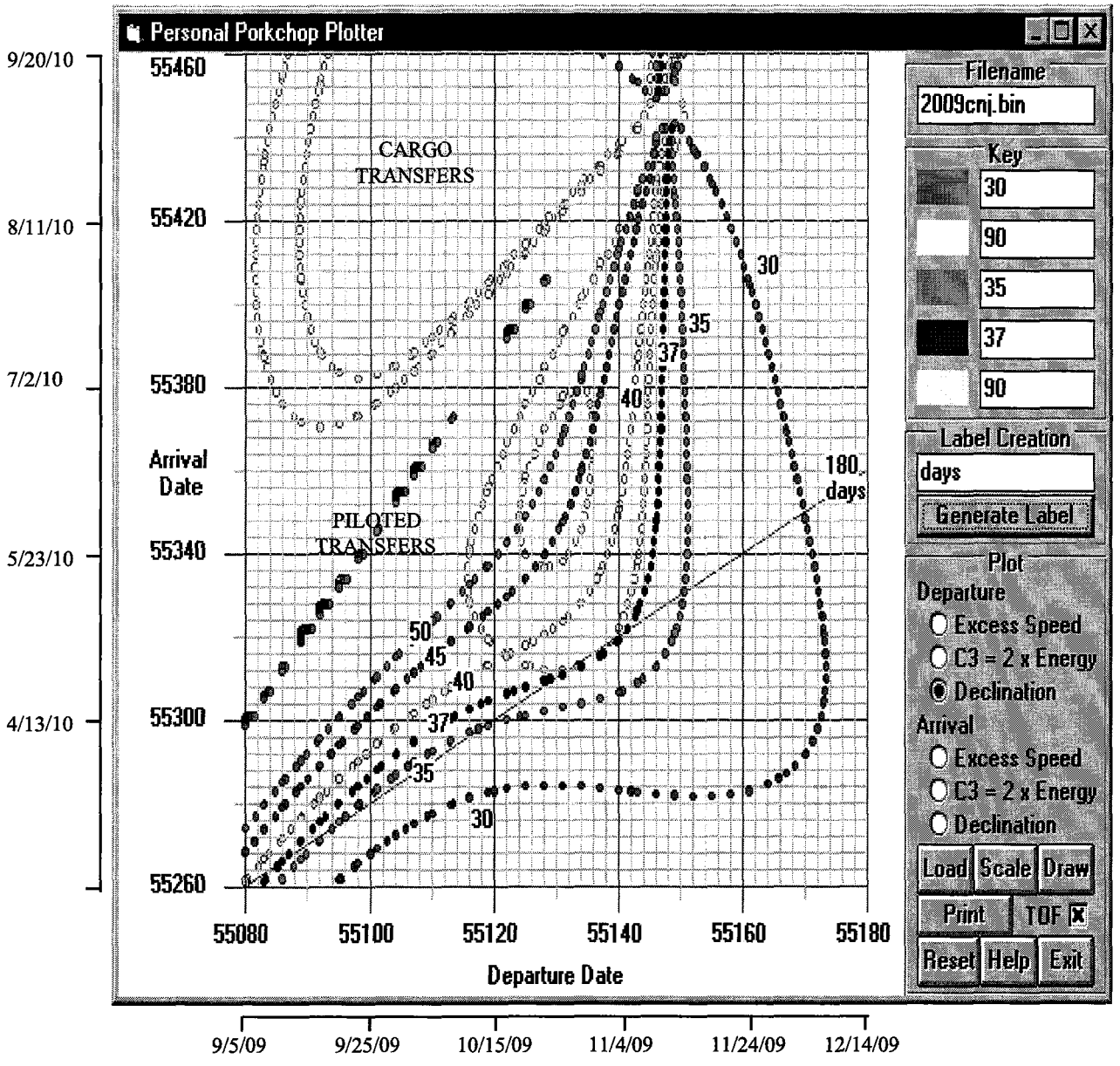
Earth-Mars Trajectories
2009 Piloted Missions
Departure Excess Speed (km/sec)



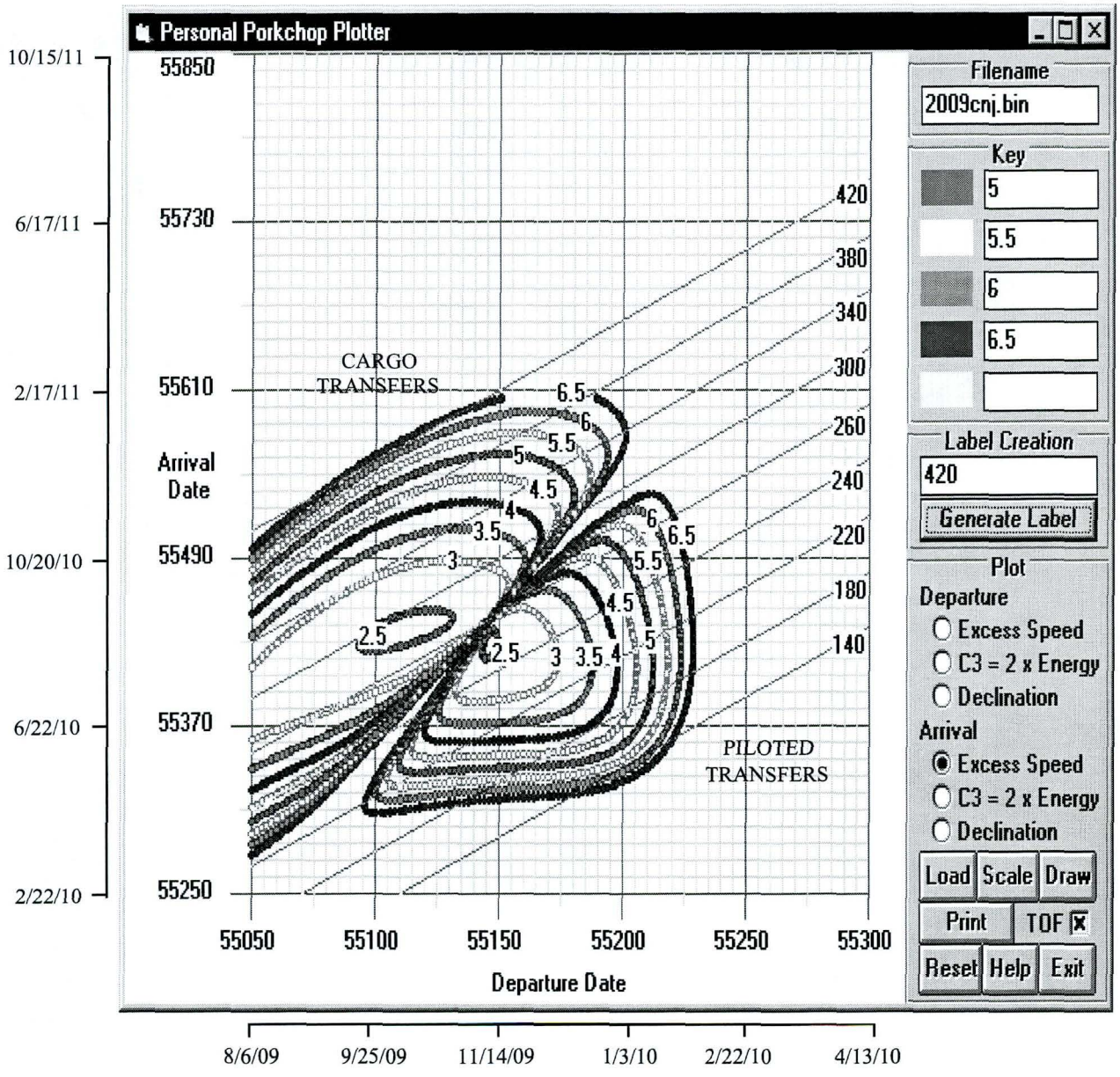
Earth-Mars Trajectories
2009 Piloted Missions
C_3 (Departure Energy) km^2/sec^2



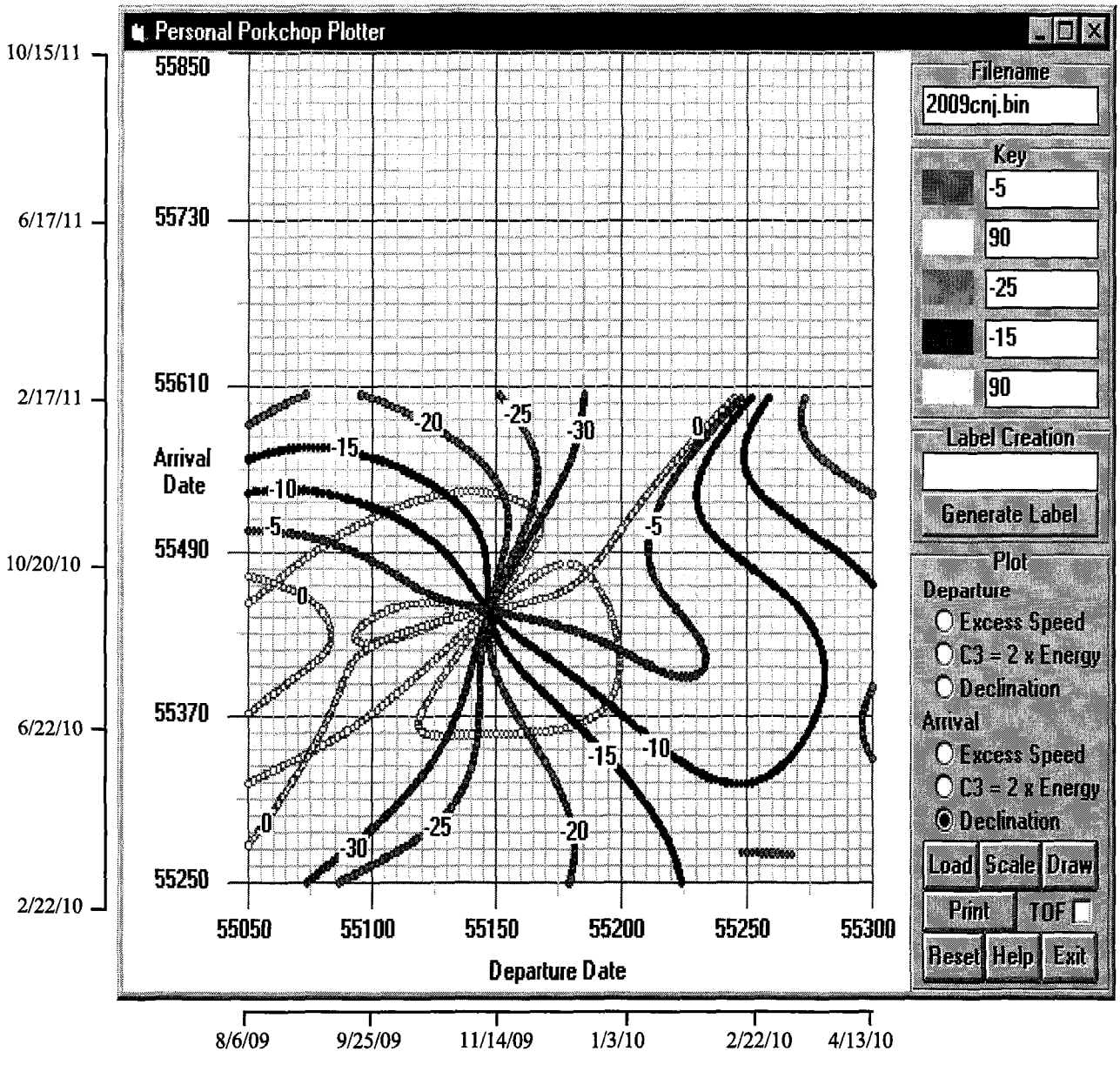
Earth-Mars Trajectories
2009 Piloted Missions
Departure Declination (Degrees)



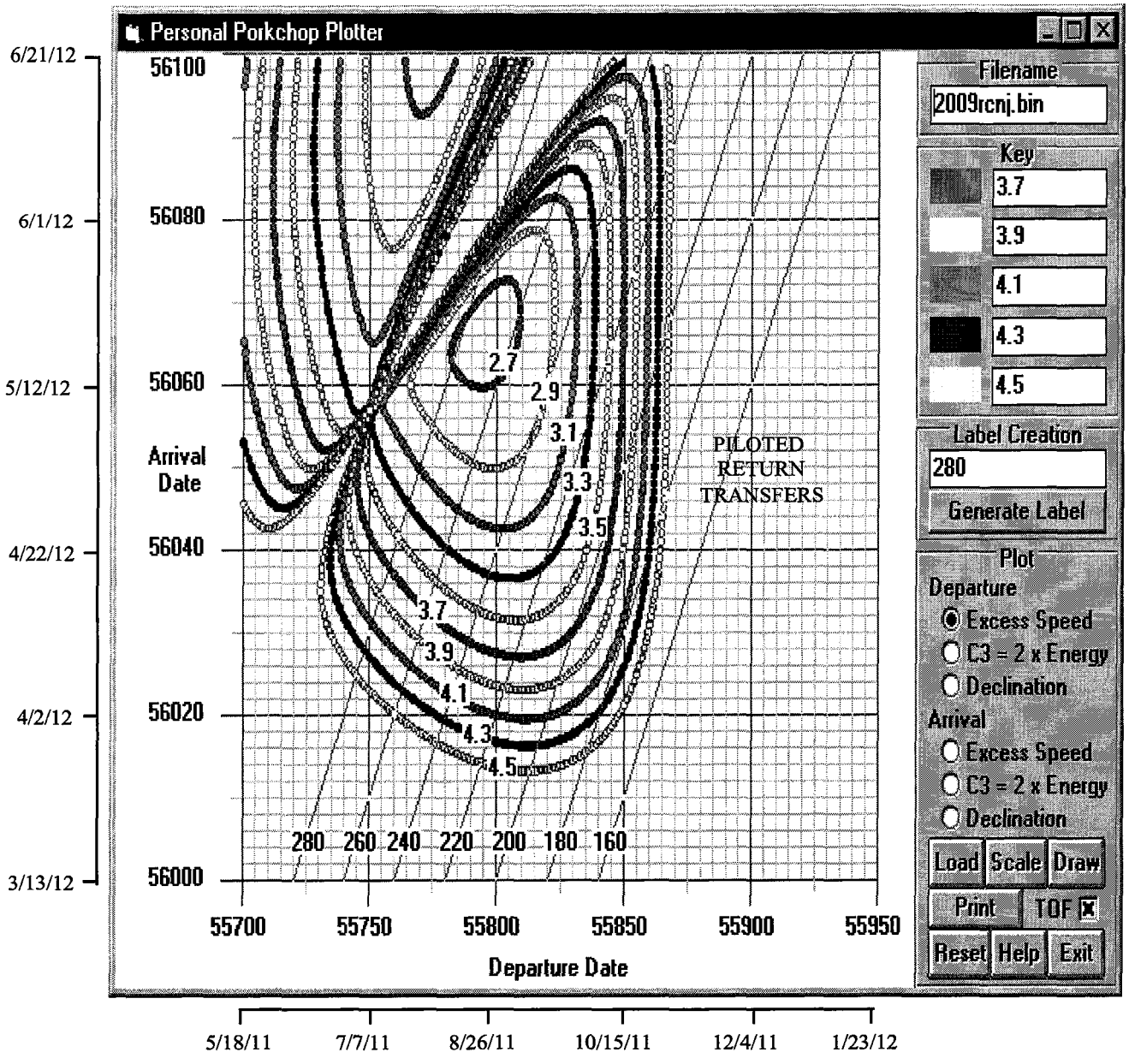
Earth-Mars Trajectories
2009 Conjunction Class
Arrival Excess Speed (km/sec)



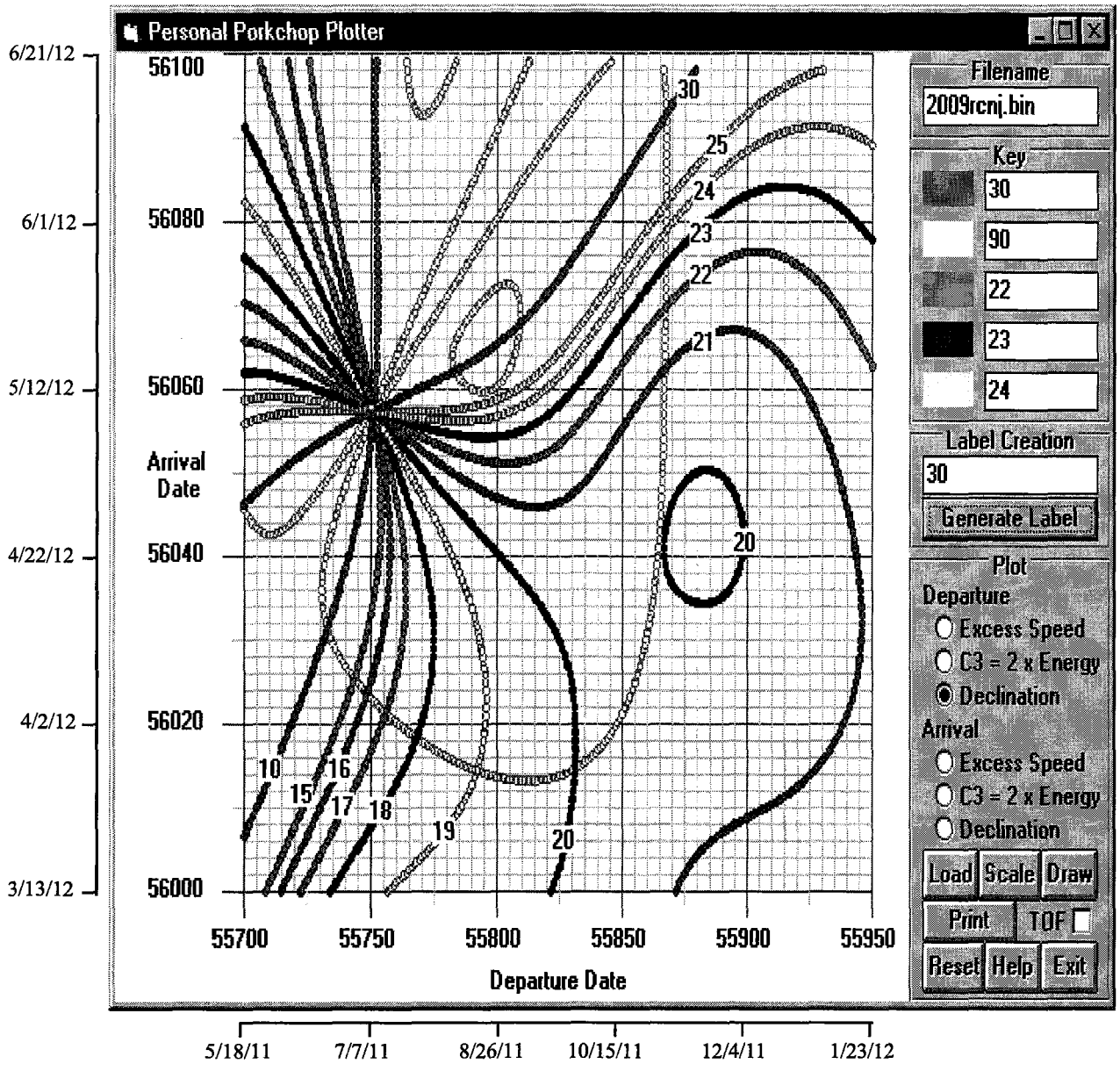
Earth-Mars Trajectories
2009 Conjuction Class
Arrival Declinations (Degrees)



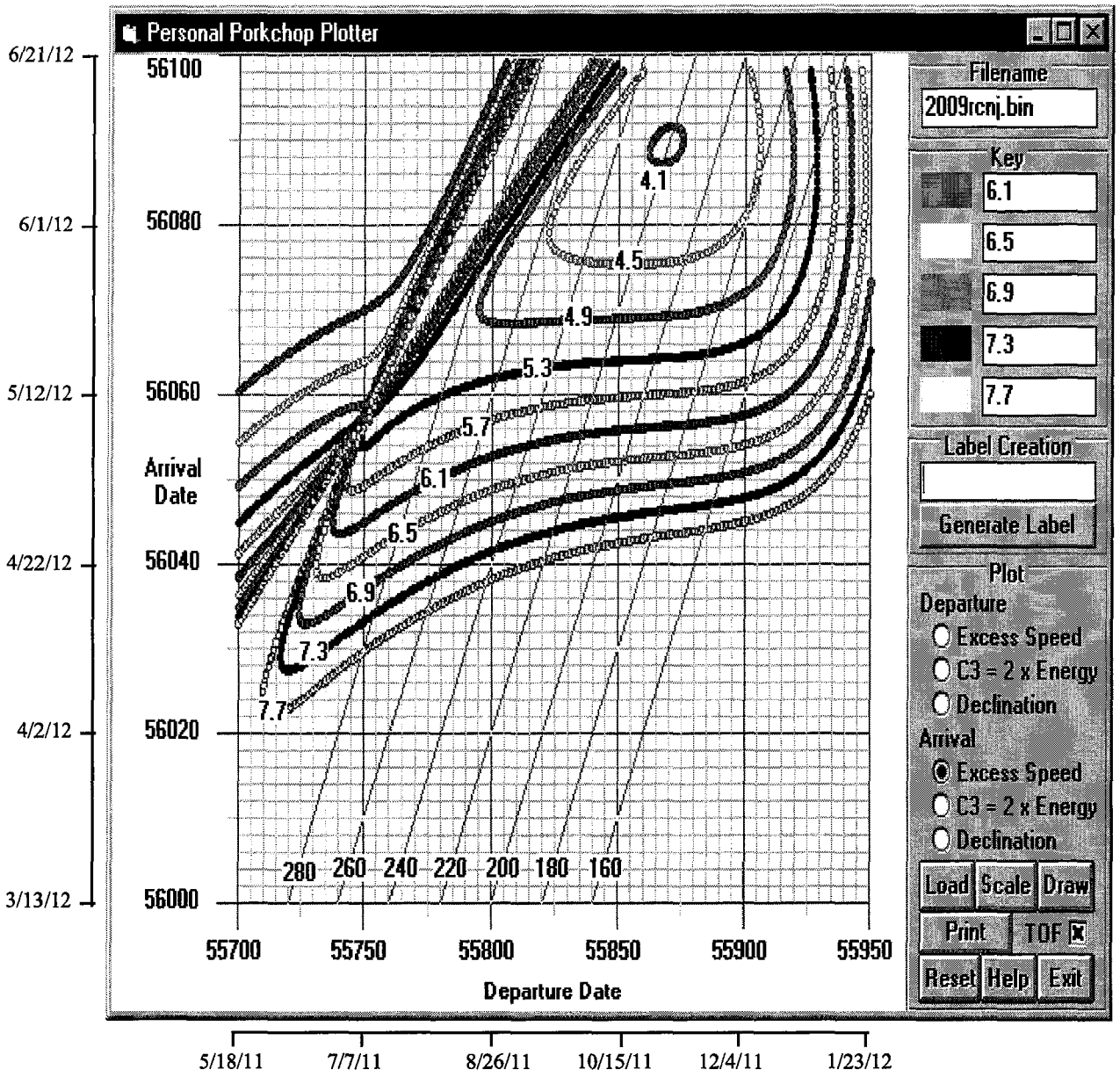
Mars-Earth Trajectories
2011 Conjunction Class
(Return from 2009 Missions)
Departure Excess Speed (km/sec)



Mars-Earth Trajectories
2011 Conjunction Class
(Return from 2009 Missions)
Departure Declination (Degrees)



Mars-Earth Trajectories
2011 Conjunction Class
(Return from 2009 Missions)
Arrival Excess Speed (km/sec)



Mars-Earth Trajectories
2011 Conjunction Class
(Return from 2009 missions)
Arrival Declination (Degrees)

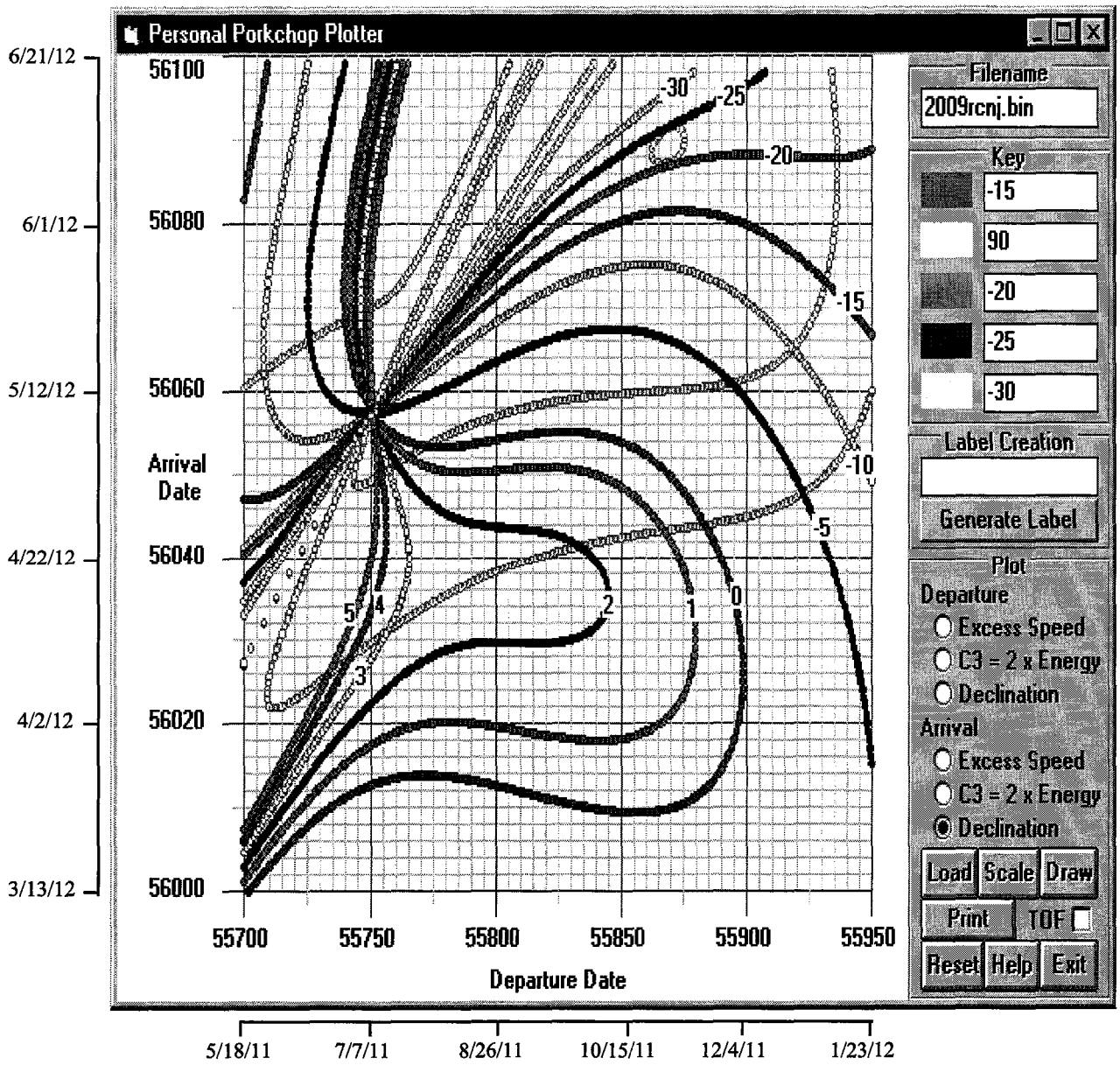
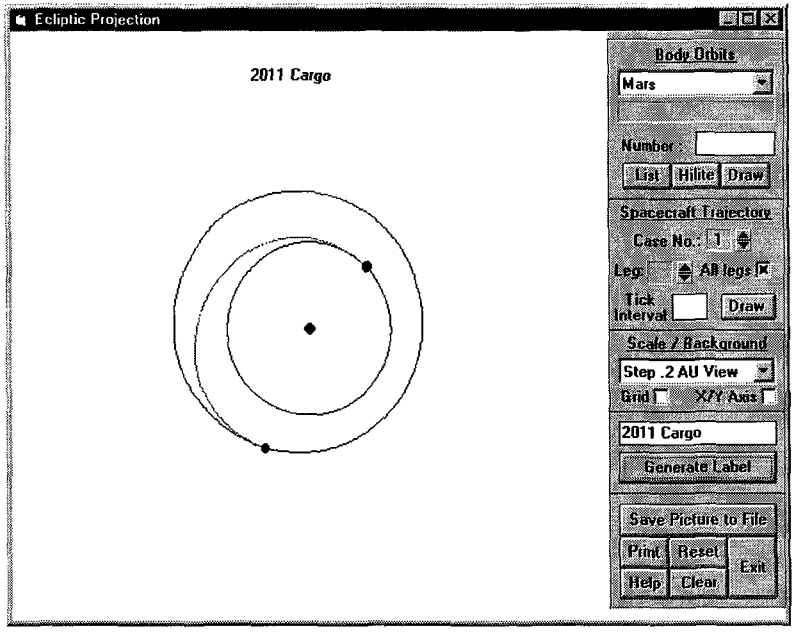
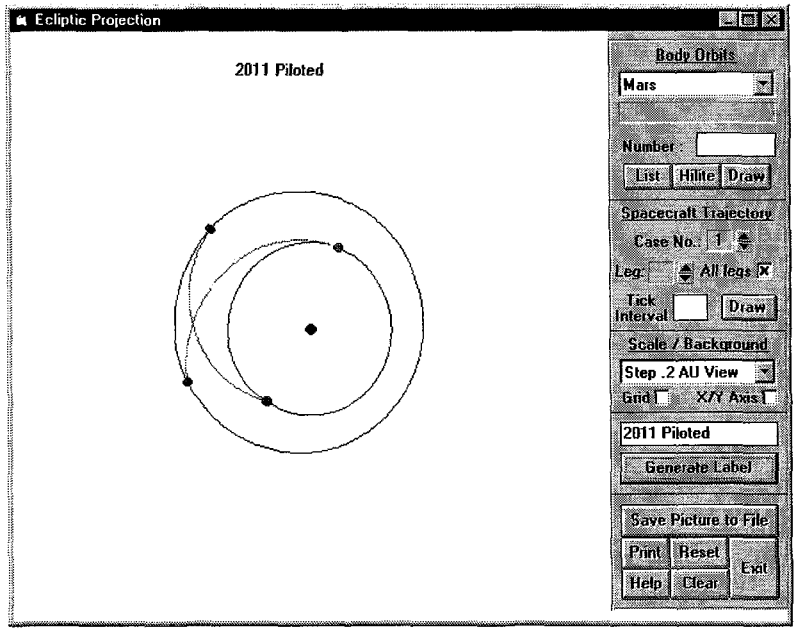


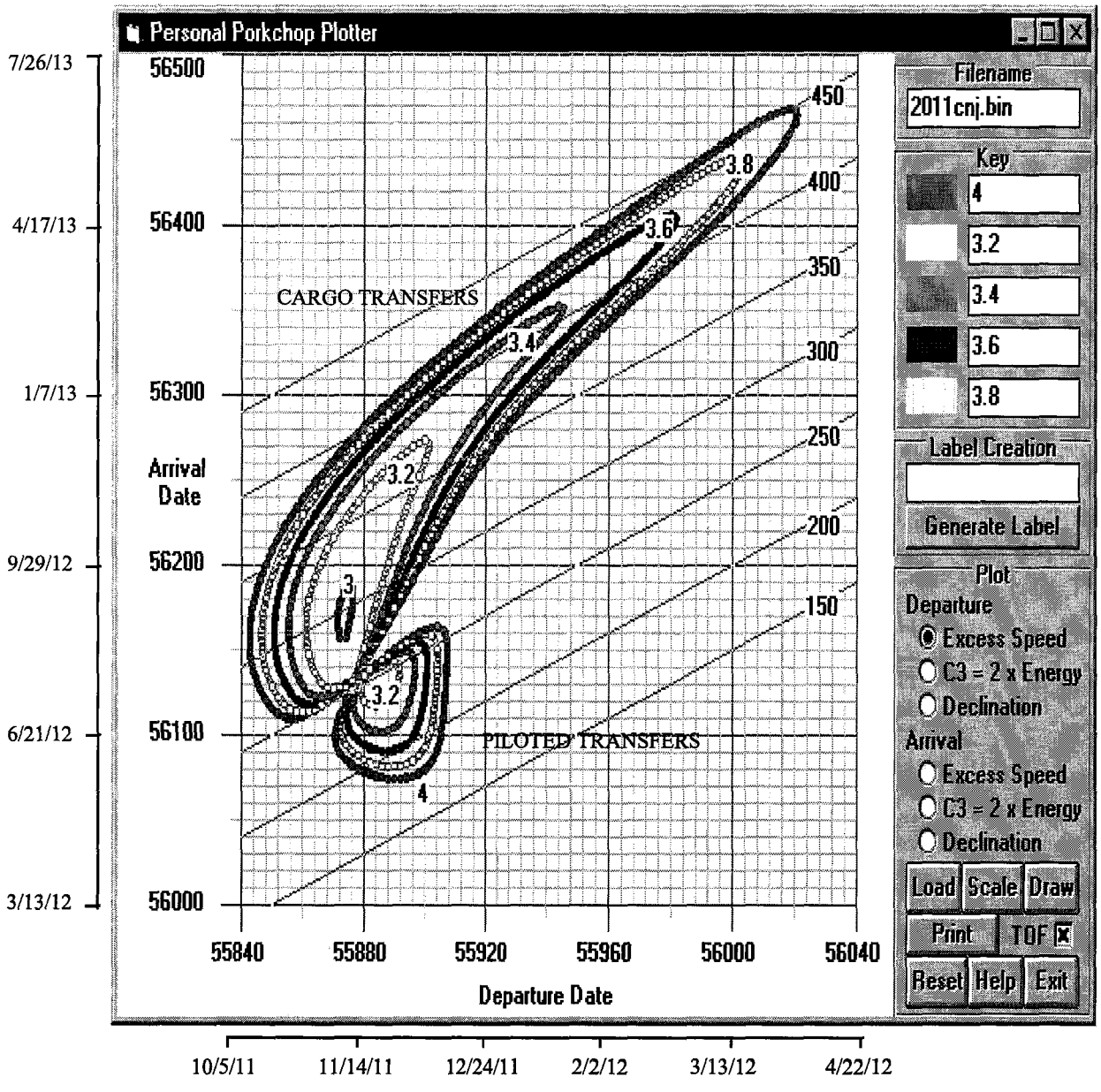
Table 10. 2011 opportunities summary.

Mission Type	TMI Date (m/d/yr)	TMI ΔV (m/sec)	Velocity Losses (m/sec)	Mars Arrival Date (m/d/yr)	Outbound Flight Time (days)	Mars Stay Time (days)	Mars Departure Date (m/d/yr)	TEI ΔV (m/sec)	Return Time (days)	Return Date (m/d/yr)	Total Mission Duration (days)	C_3 (km^2/sec^2)	Total ΔV (m/s)	Depart. V_∞ @ Earth (km/sec)	Arrival V_∞ @ Mars (km/sec)	Arrival Velocity @ Mars (km/sec)	Depart. V_∞ @ Mars (km/sec)	Arrival V_∞ @ Earth (km/sec)	Arrival Velocity @ Earth (km/sec)
Cargo 1	11/8/11	3,673	92	8/31/12	297	—	—	—	—	—	—	8.95	3,673	2.9911	2.751	5.647	—	—	—
Cargo 2	11/8/11	3,695	113	8/31/12	297	—	—	—	—	—	—	8.95	3,695	2.9911	2.751	5.647	—	—	—
Piloted	12/2/11	4,019	132	5/30/12	180	538	11/19/13	1,476	180	5/18/14	898	15.92	5,495	3.9894	7.073	8.623	3.688	9.312	14.47

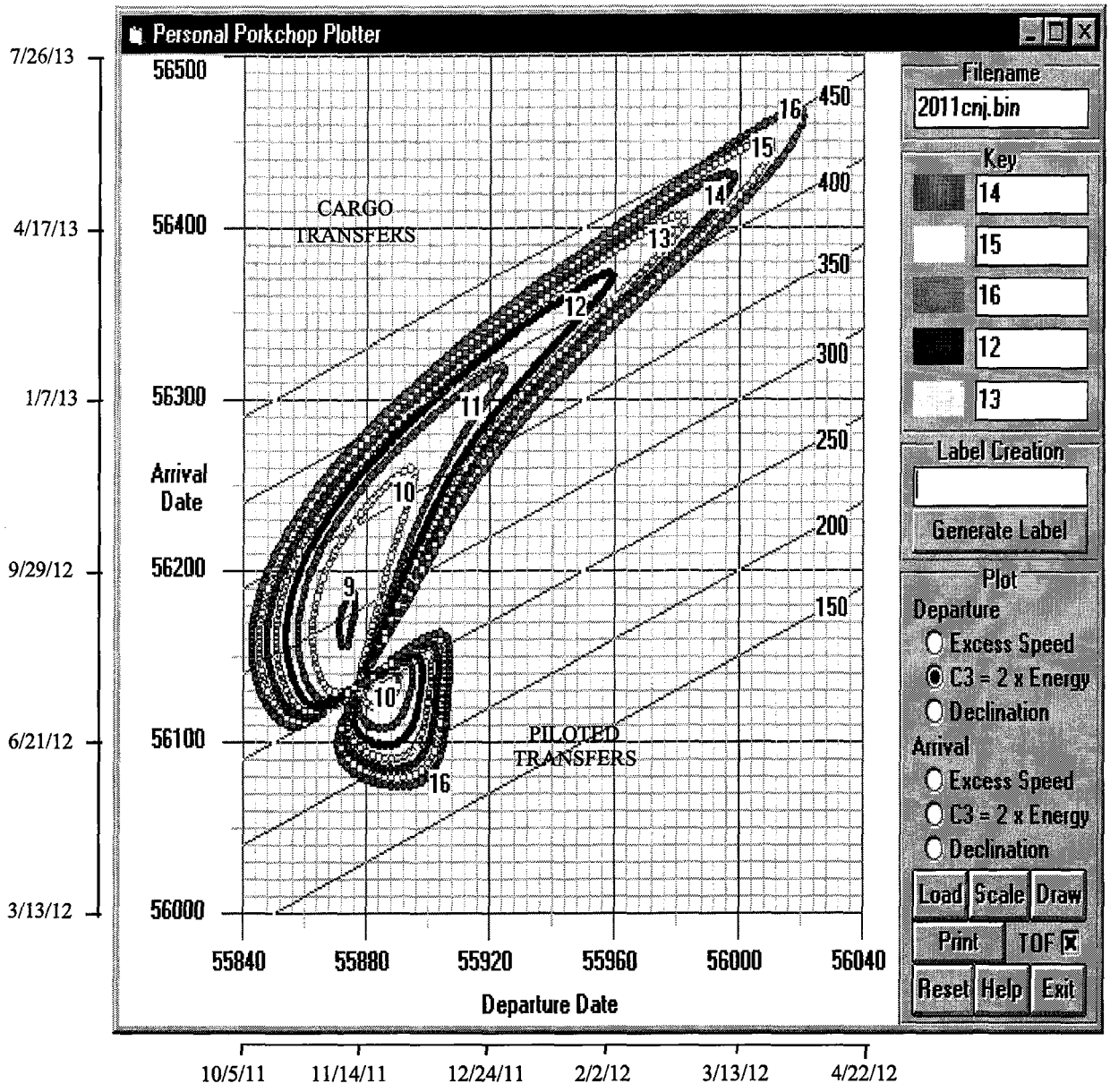




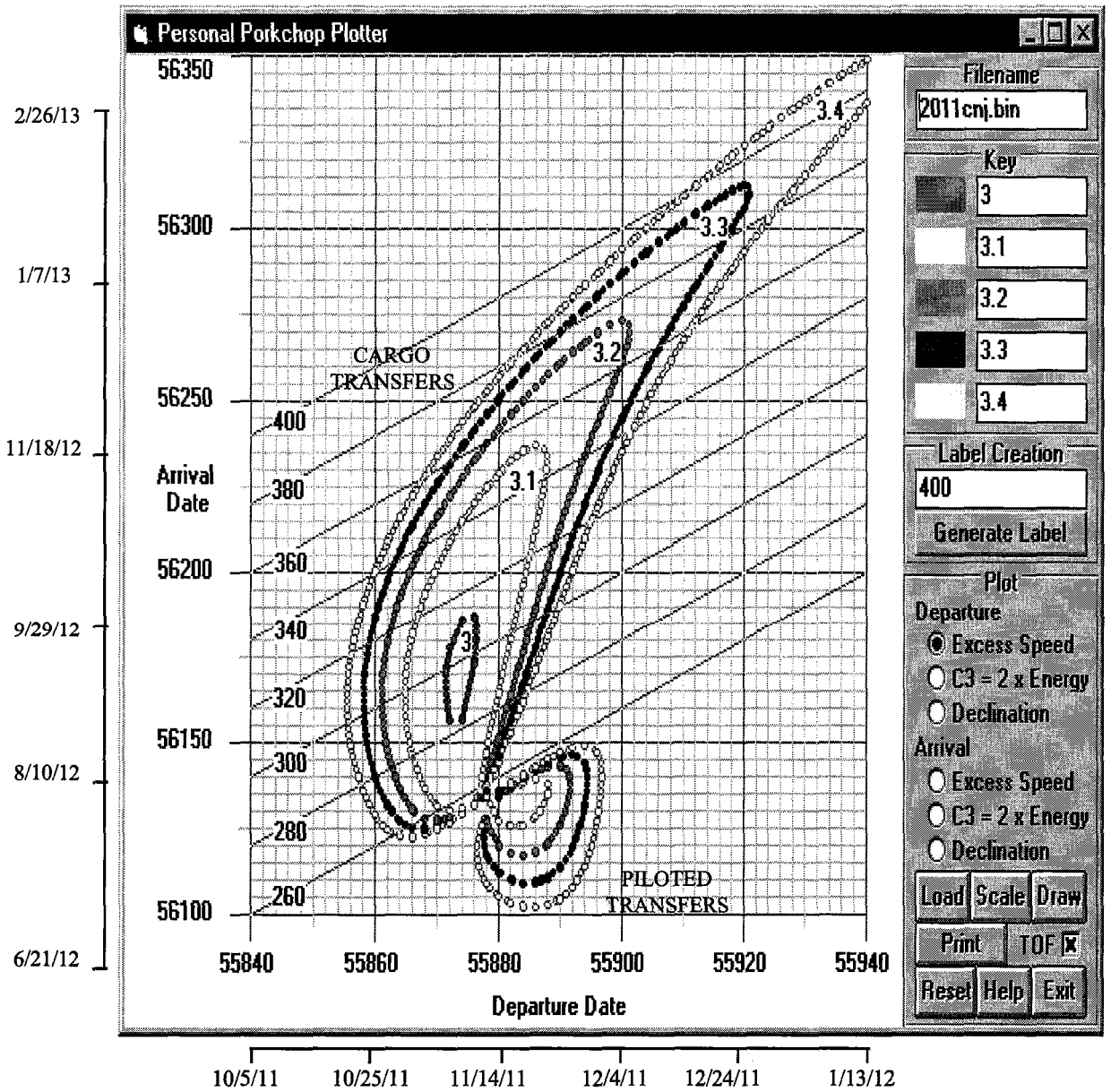
Earth-Mars Trajectories
2011 Conjunction Class
Departure Excess Speed (km/sec)



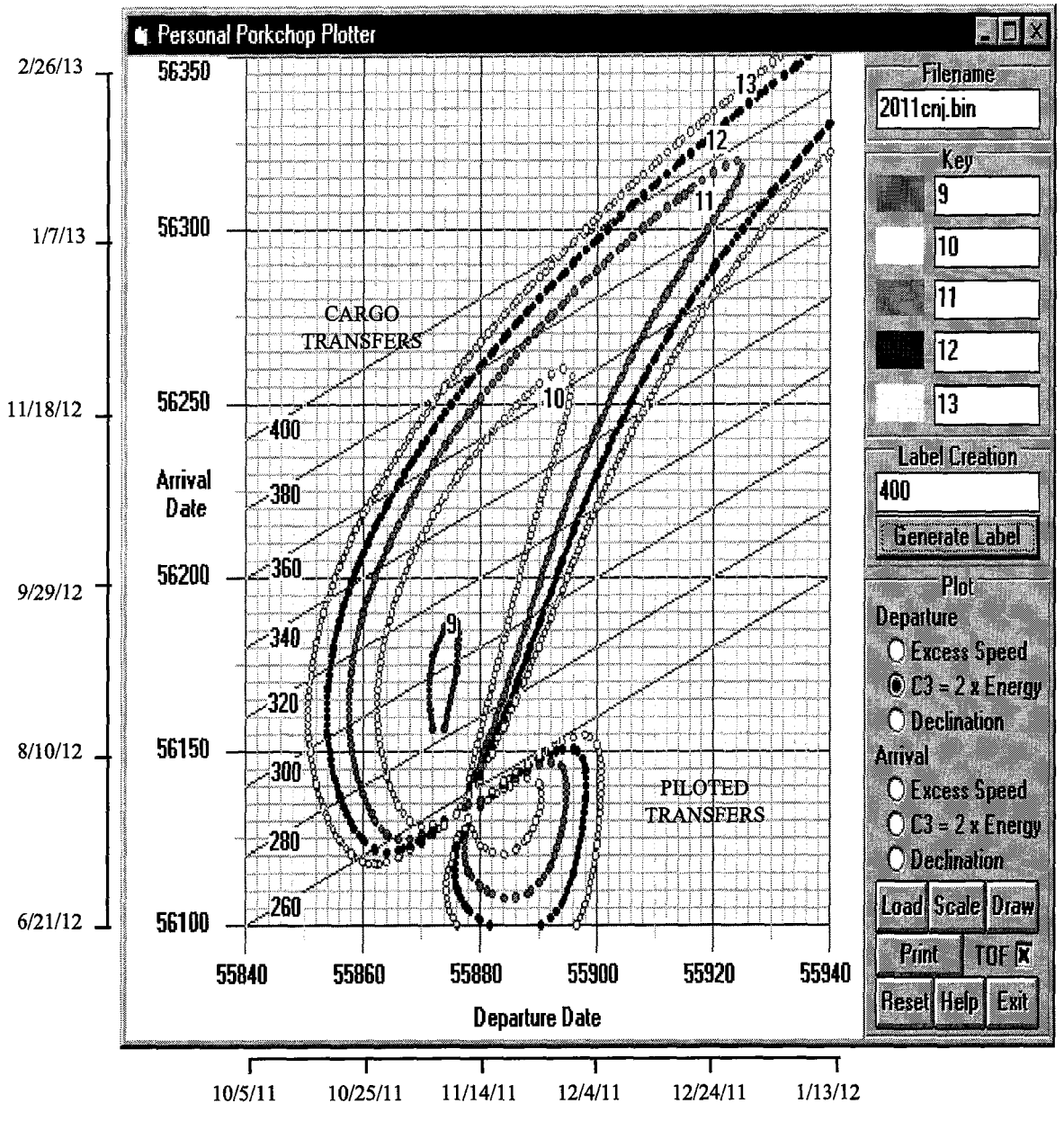
Earth-Mars Trajectories
2011 Conjunction Class
C_3 (Departure Energy) km^2/sec^2



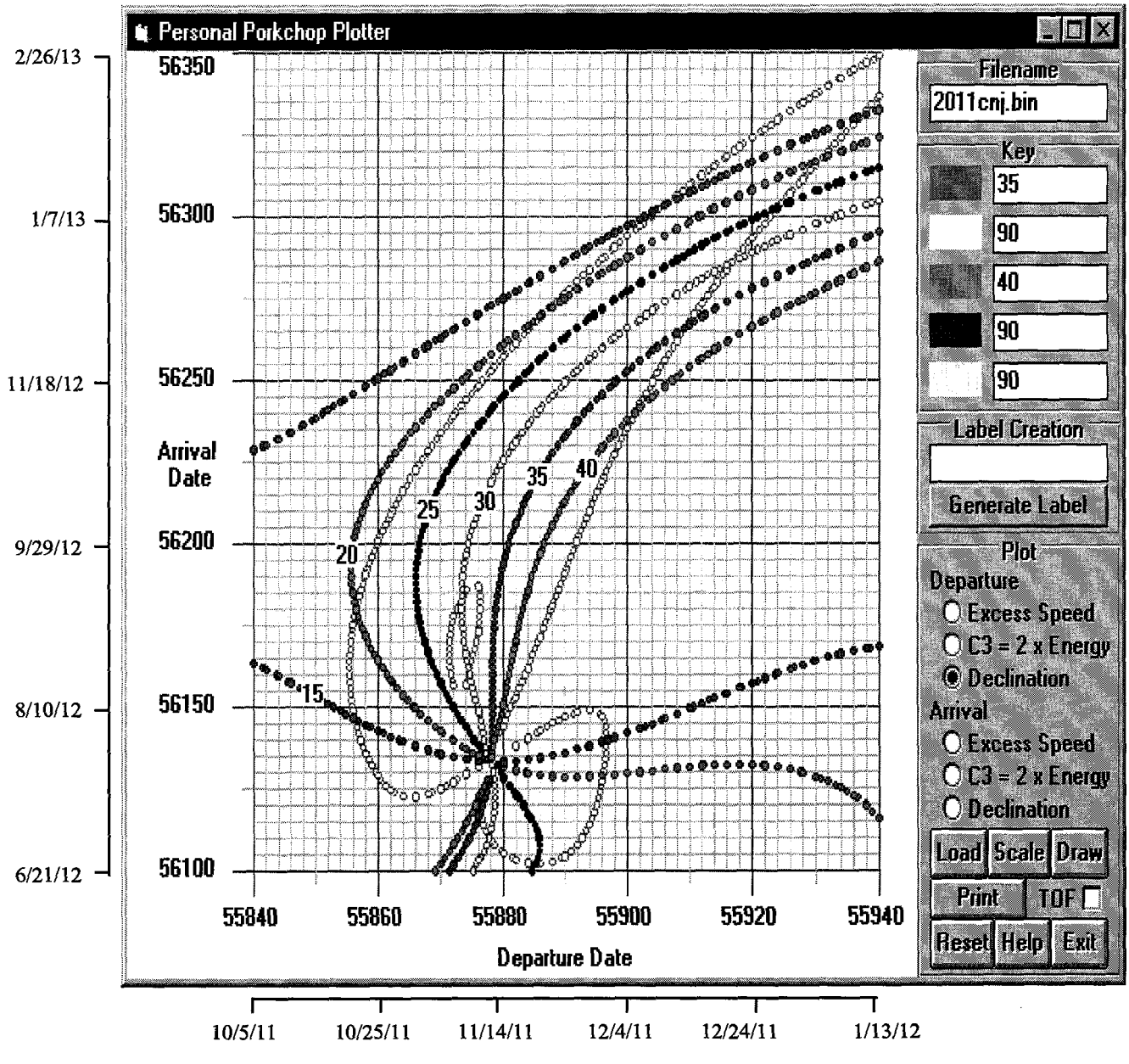
Earth-Mars Trajectories
2011 Cargo Missions
Departure Excess Speed (km/sec)



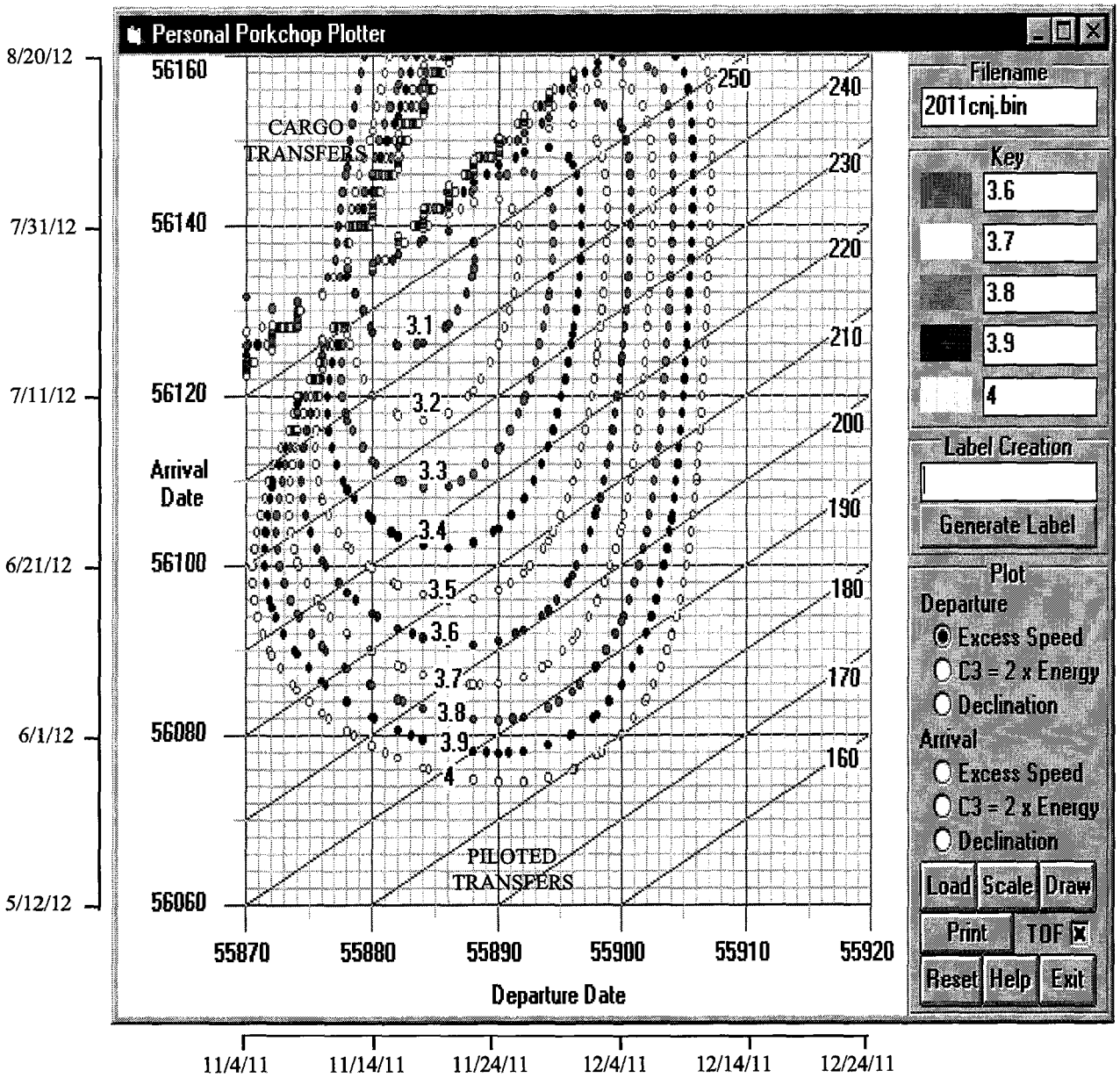
Earth-Mars Trajectories
2011 Cargo Missions
C_3 (Departure Energy) km^2/sec^2



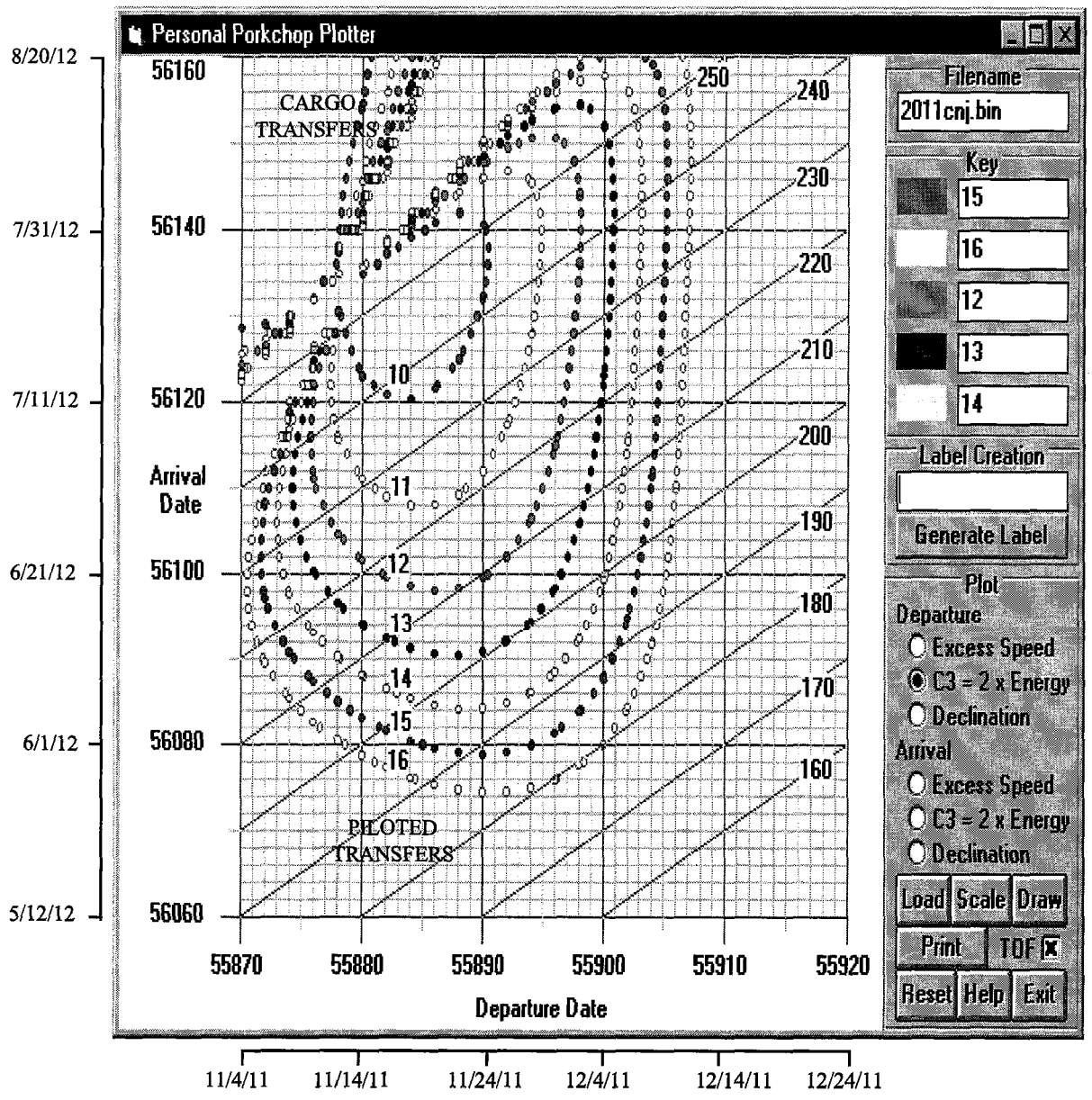
Earth-Mars Trajectories
2011 Cargo Missions
Departure Declination (Degrees)



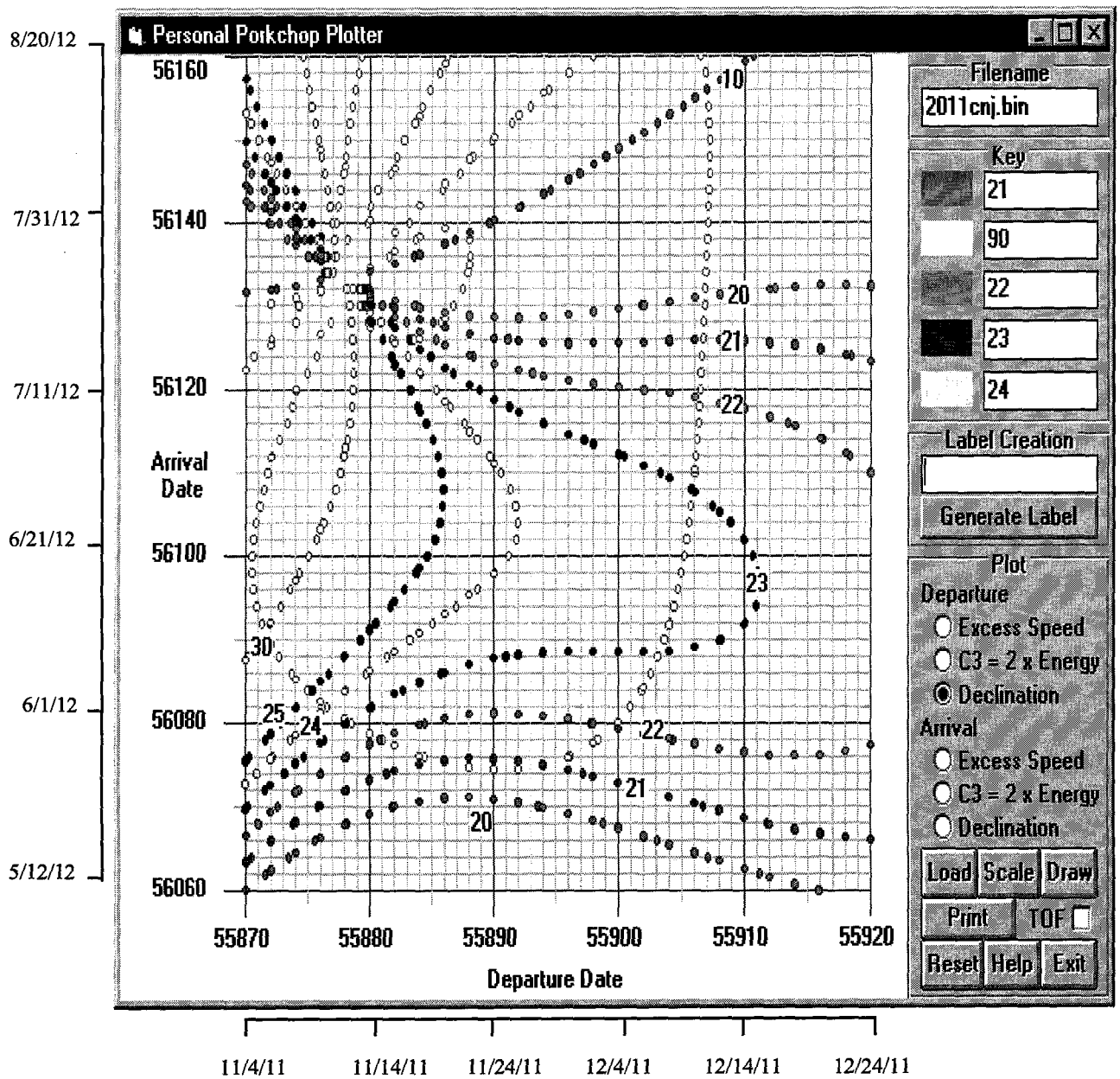
Earth-Mars Trajectories
2011 Piloted Missions
Departure Excess Speed (km/sec)



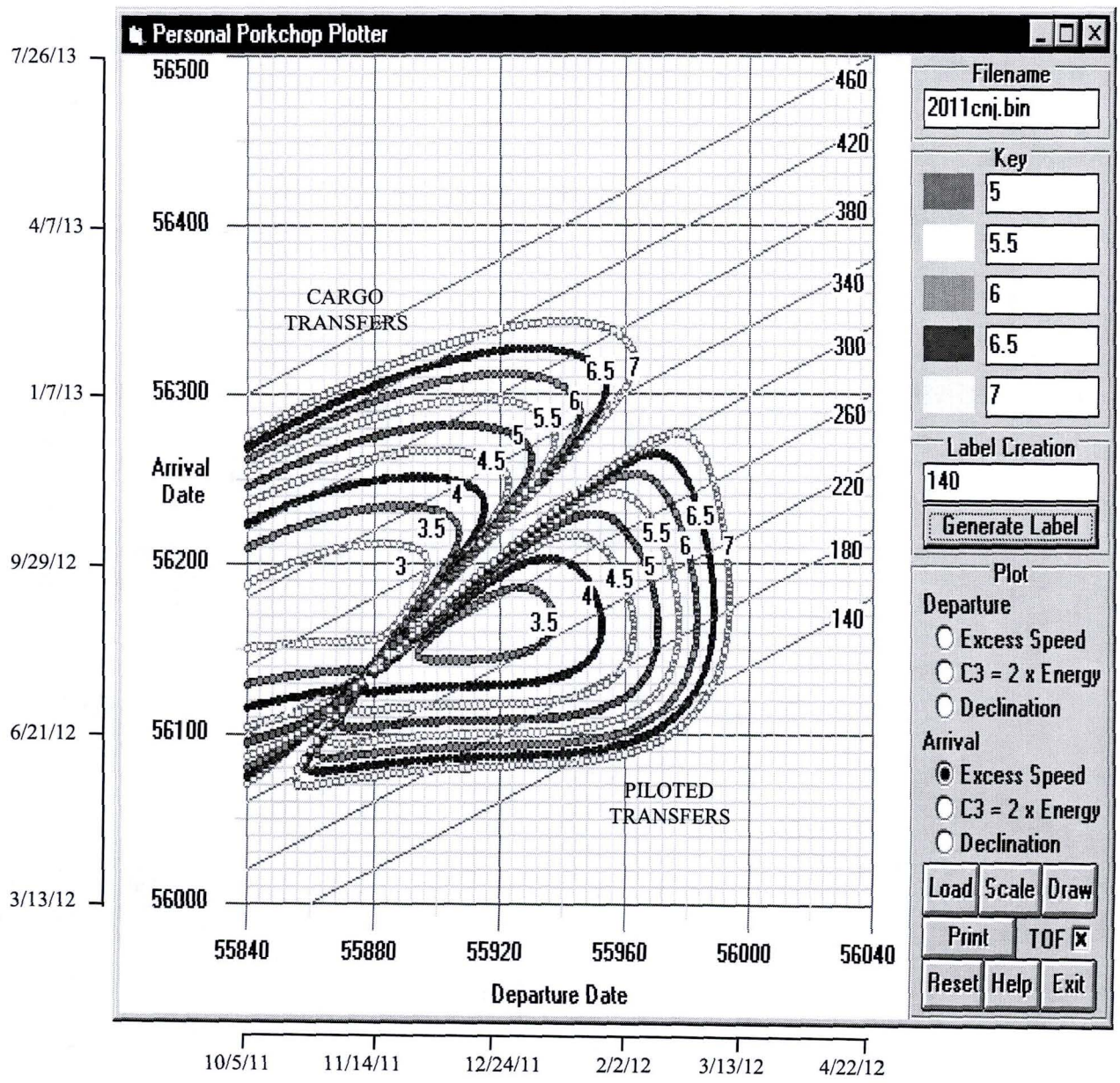
Earth-Mars Trajectories
2011 Piloted Missions
C_3 (Departure Energy) km^2/sec^2



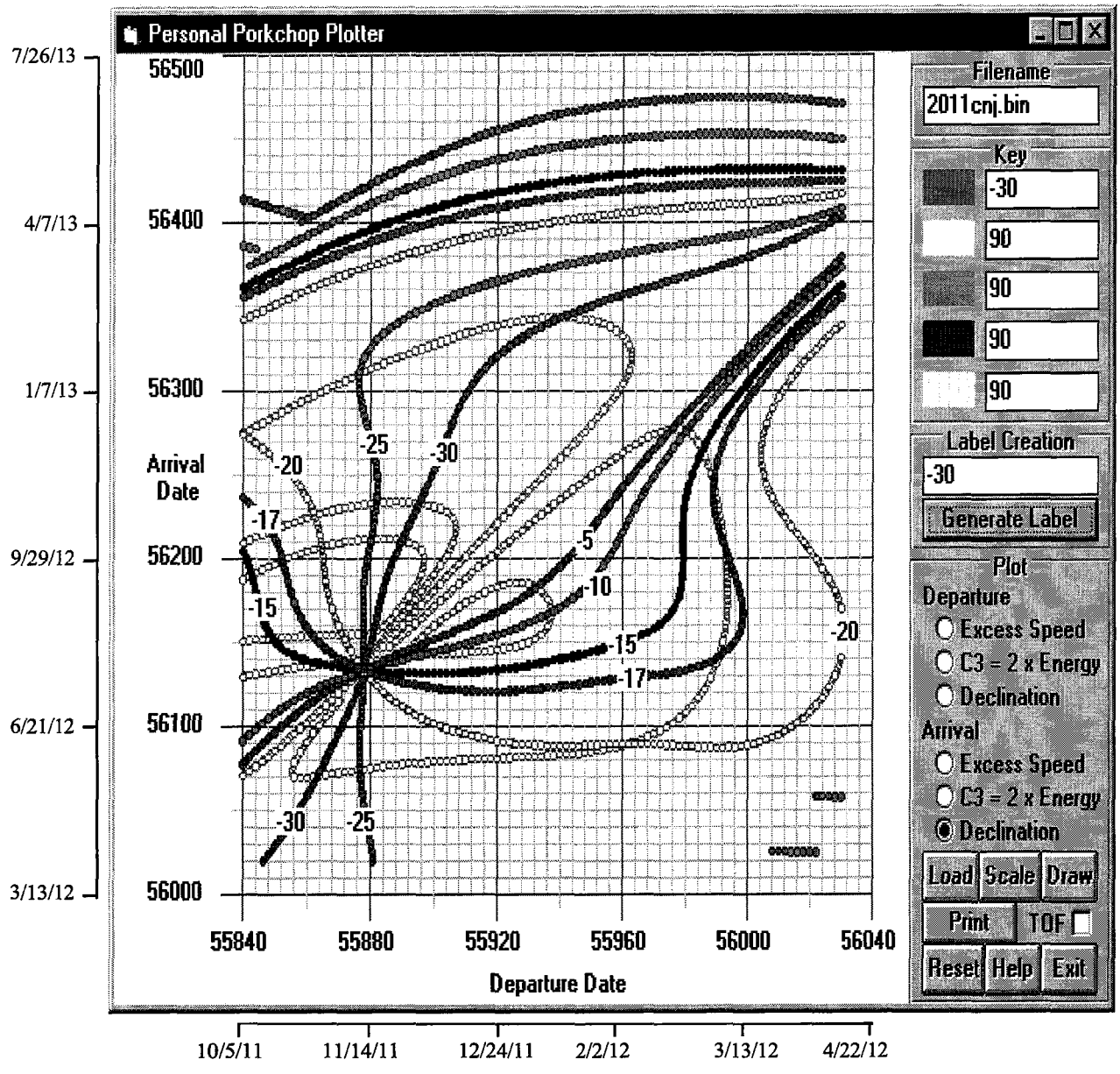
Earth-Mars Trajectories
2011 Piloted Missions
Departure Declination (Degrees)



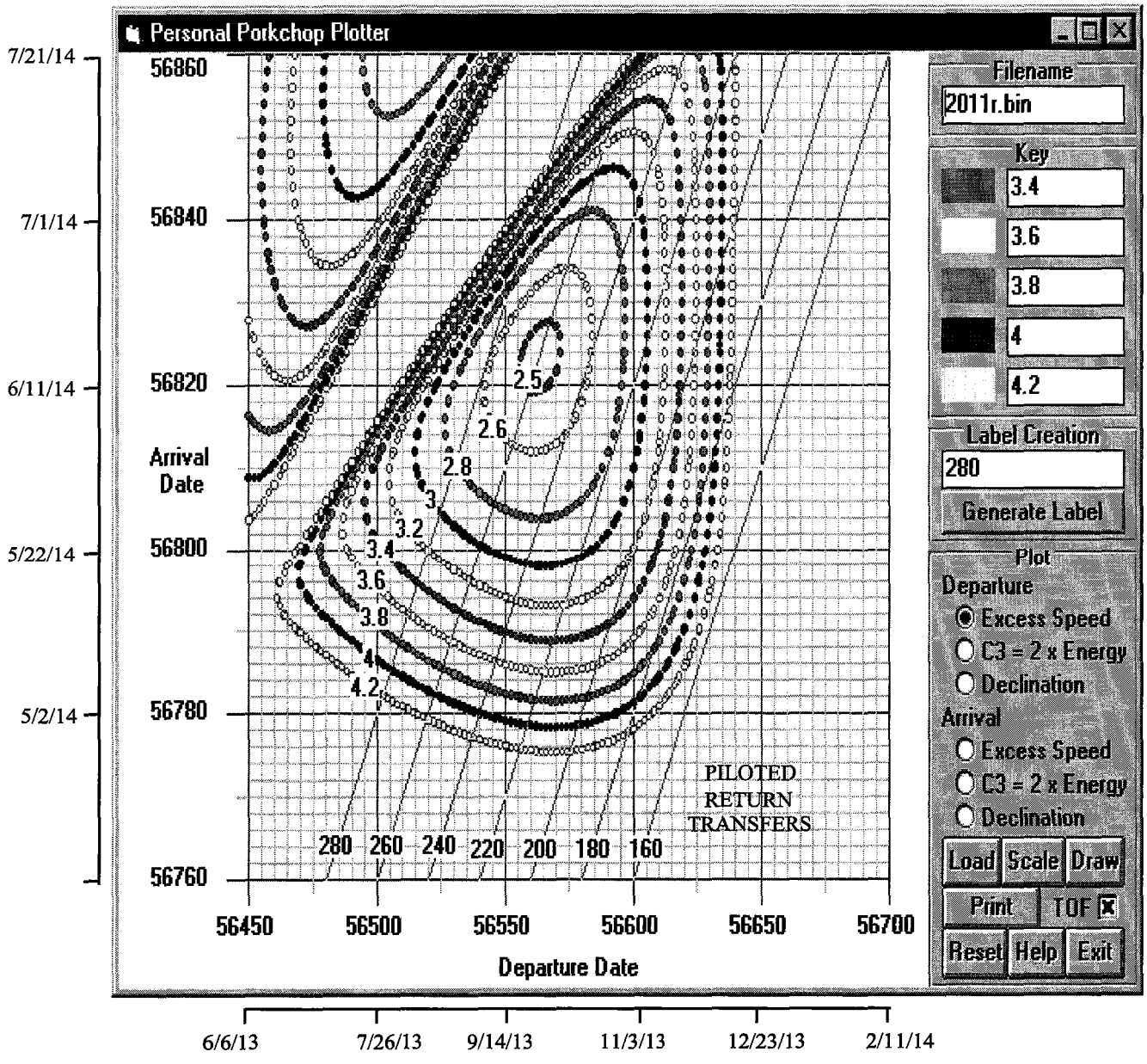
Earth-Mars Trajectories
2011 Conjunction Class
Arrival Excess Speed (km/sec)



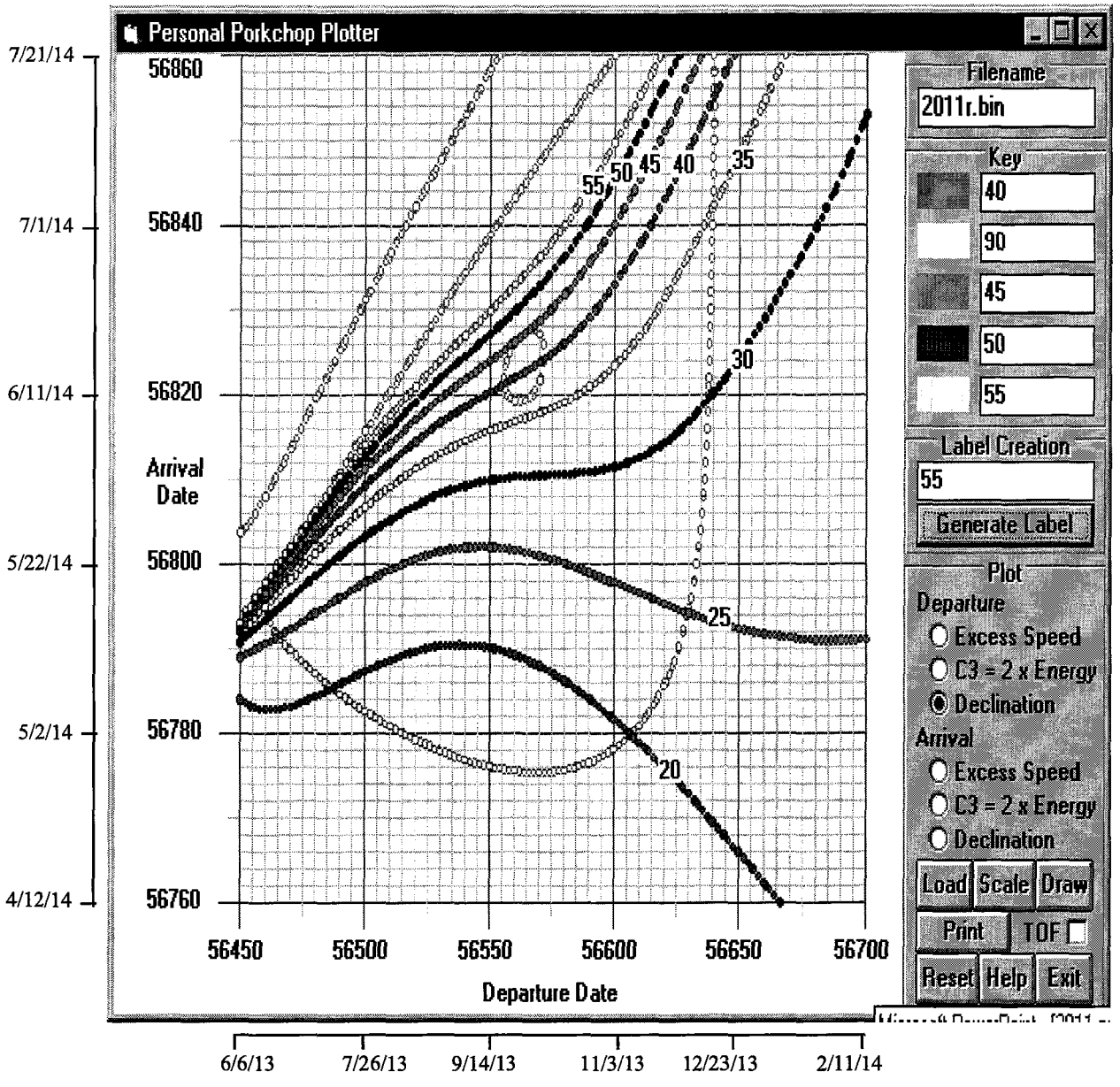
Earth-Mars Trajectories
2011 Conjunction Class
Arrival Declination (Degrees)



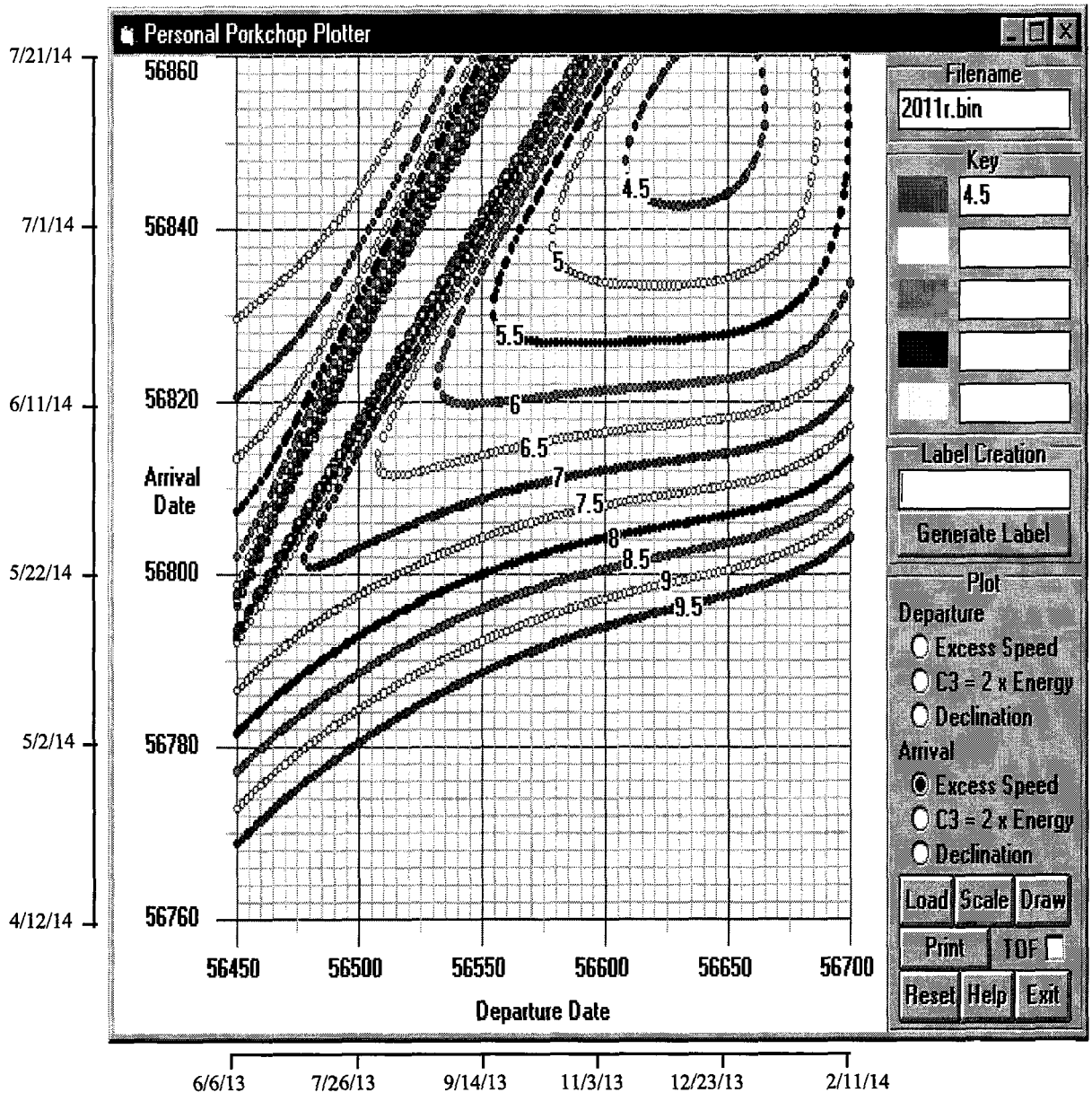
Mars-Earth Trajectories
2013 Conjunction Class
(Returns from 2011 Missions)
Departure Excess Speed (km/sec)



Mars-Earth Trajectories
2013 Conjunction Class
(Returns from 2011 Missions)
Departure Declination (Degrees)



Mars-Earth Trajectories
2013 Conjunction Class
(Returns from 2011 Missions)
Arrival Excess Speed (km/sec)



Mars-Earth Trajectories
2013 Conjunction Class
(Returns from 2011 Missions)
Arrival Declination (Degrees)

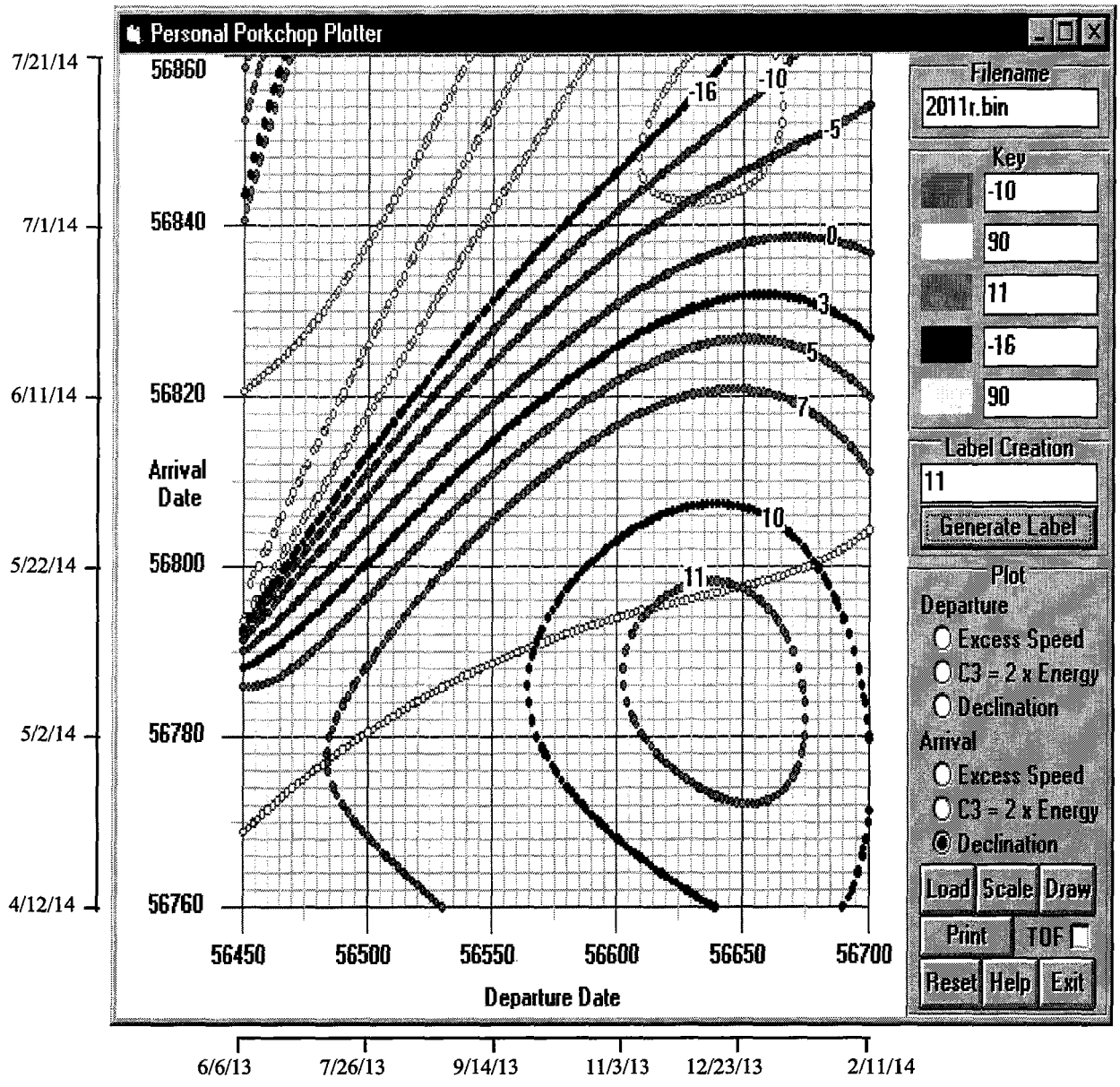


Table 11. 2014 opportunities summary.

Mission Type	TMI Date (m/d/yr)	TMI ΔV (m/sec)	Velocity Losses (m/sec)	Mars Arrival Date (m/d/yr)	Outbound Flight Time (days)	Mars Stay Time (days)	Mars Departure Date (m/d/yr)	TEI ΔV (m/sec)	Return Time (days)	Return Date (m/d/yr)	Total Mission Duration (days)	C_3 (km^2/sec^2)	Total ΔV (m/sec)	Depart. V_∞@ Earth (km/sec)	Arrival V_∞@ Mars (km/sec)	Arrival Velocity @ Mars (km/sec)	Depart. V_∞@ Mars (km/sec)	Arrival V_∞@ Earth (km/sec)	Arrival Velocity @ Earth (km/sec)
Cargo 1	12/31/13	3,665	91	11/24/14	328	—	—	—	—	—	—	8.78	3,665	2.963	4.418	6.621	—	—	—
Cargo 2	12/31/13	3,686	112	11/24/14	328	—	—	—	—	—	—	8.78	3,686	2.963	4.418	6.621	—	—	—
Piloted[1]	1/4/14	3,782	108	7/3/14	180	553	1/7/16	1,074	180	7/5/16	913	11.04	4,856	3.323	6.785	8.388	2.989	7.342	13.285
Piloted	1/20/14	4,019	132	6/30/14	161	573	1/24/16	1,476	154	6/26/16	888	15.92	5,495	3.989	7.167	8.700	3.688	8.910	14.212
Piloted[2]	1/13/14	4,018	131	6/16/14	154	587	1/24/16	1,476	154	6/26/16	895	15.92	5,494	3.989	8.564	9.882	3.688	8.910	14.212
Piloted[3]	1/22/14	4,018	131	7/21/14	180	568	2/9/16	1,476	180	8/7/16	928	15.92	5,494	3.989	5.523	7.404	3.688	4.431	11.926

1) Optimal piloted trajectory (minimum initial mass)

2) Entry Velocity Limit of 8.7 km/sec at Mars exceeded

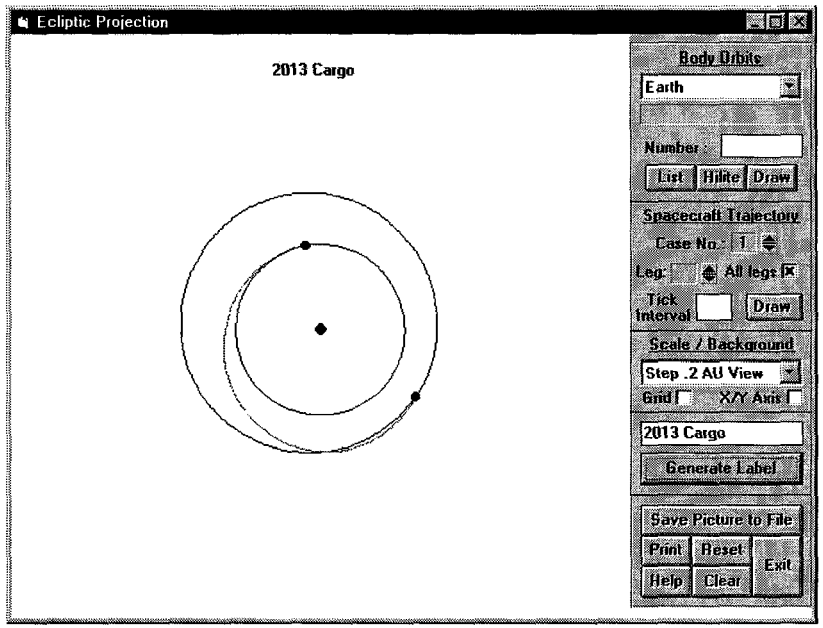
3) Latest possible launches designed to 2011/180 day C_3s

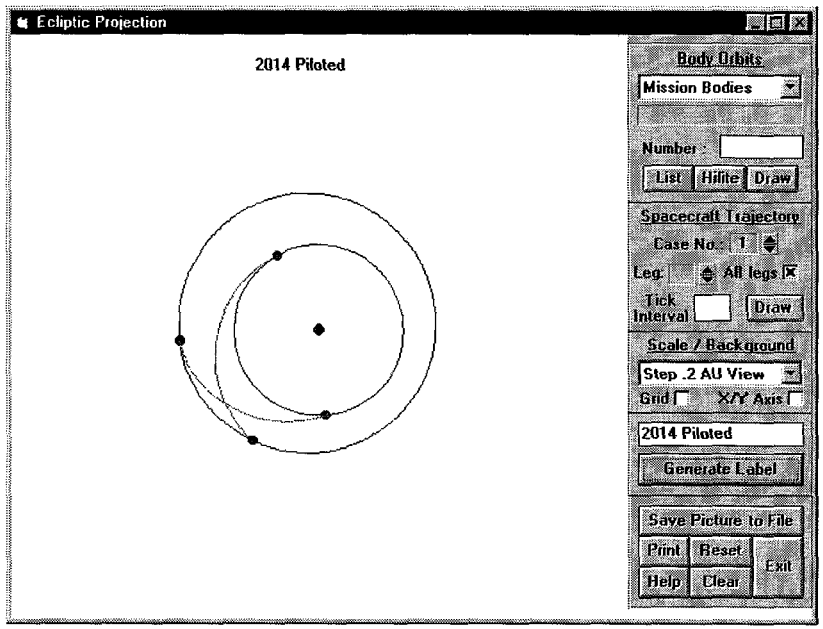
3-day Earth-Mars Departure Window:

Depart:	TOF	Arrival:
1/20/14	161	6/30/14
1/22/14	180	7/21/14

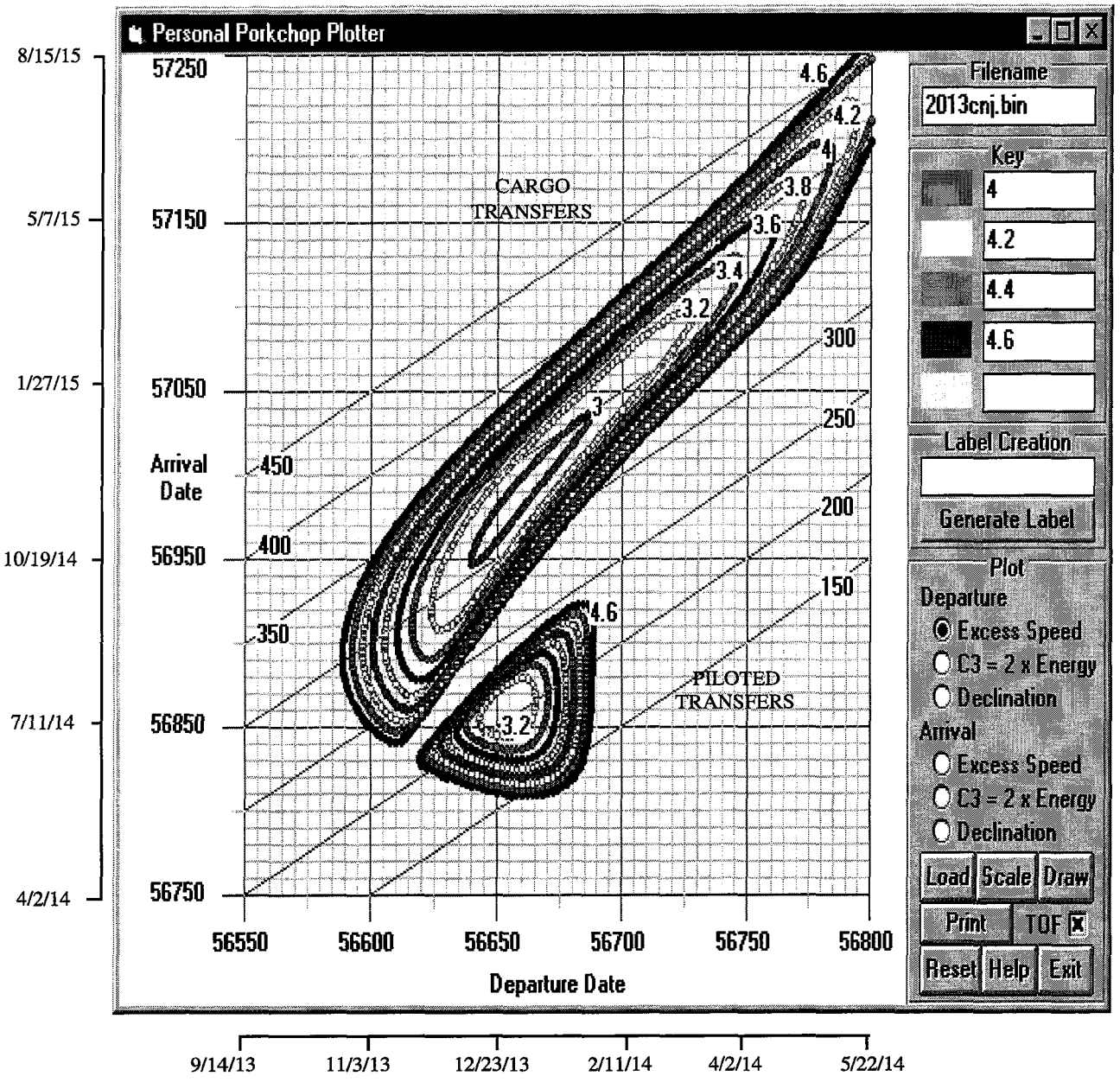
17-day Mars-Earth Return Window:

Depart:	TOF	Arrival:
1/24/16	154	6/26/16
2/9/16	180	8/7/16

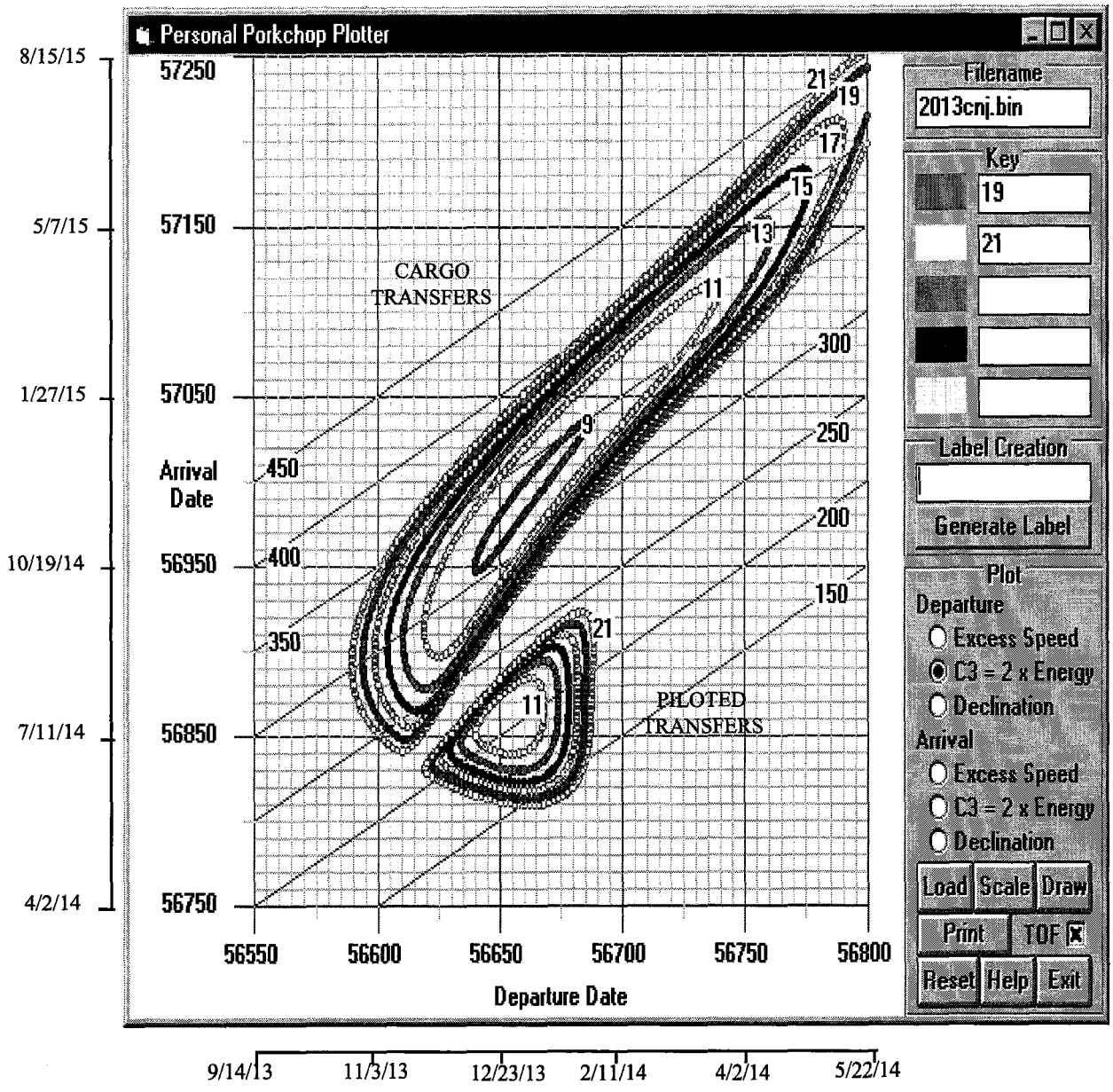




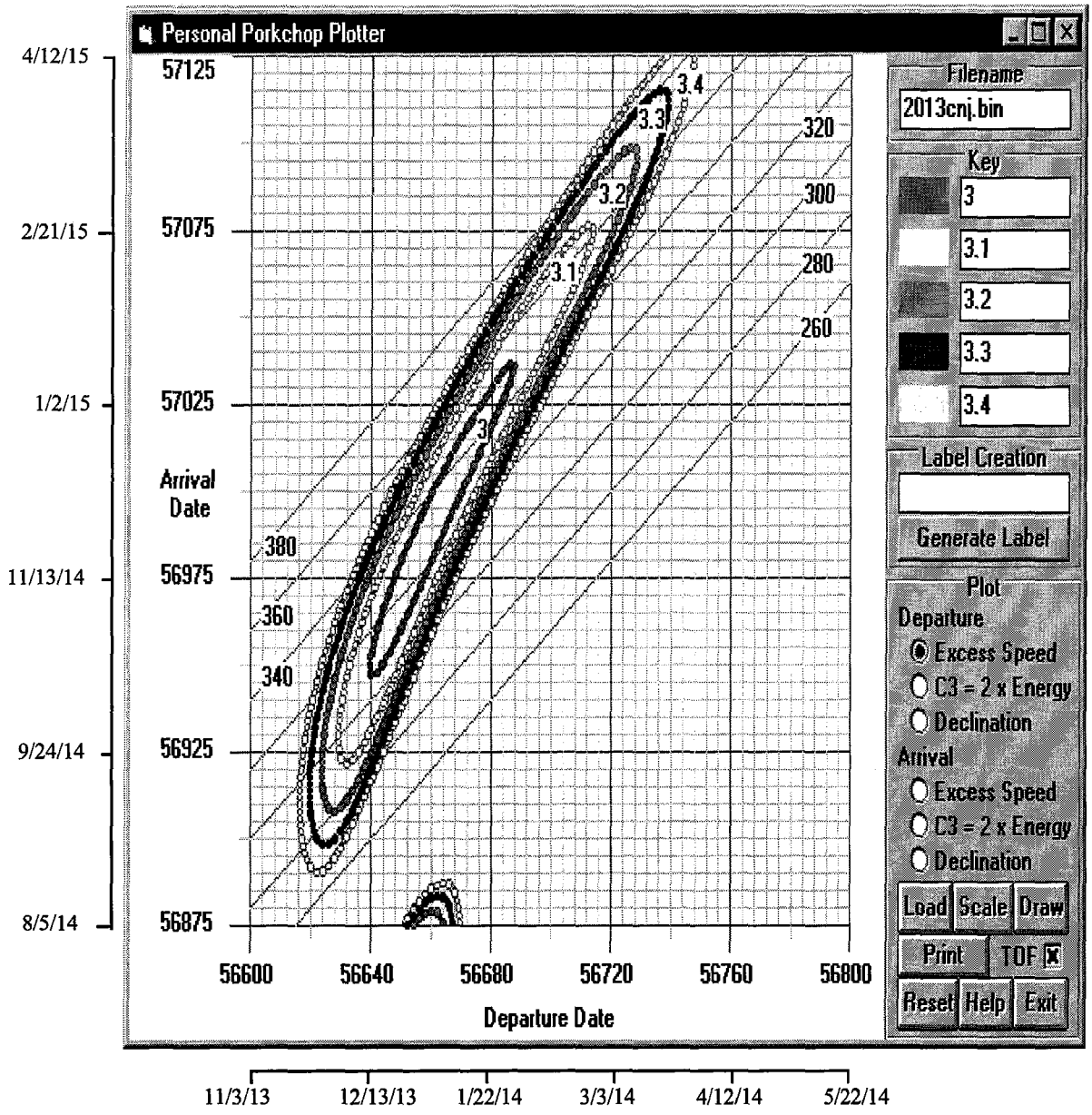
Earth-Mars Trajectories
2013/14 Conjunction Class
Departure Excess Speed (km/sec)



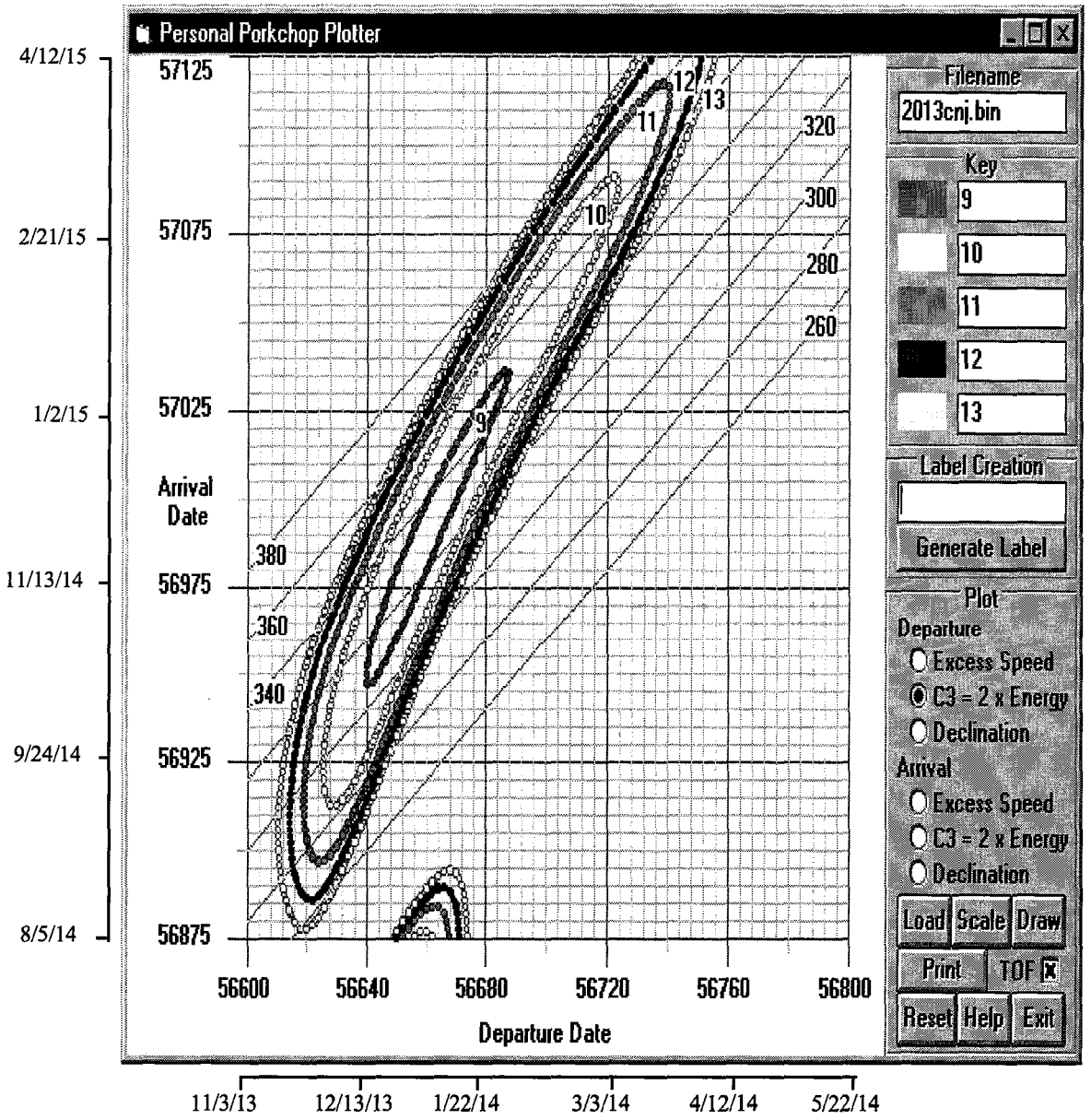
Earth-Mars Trajectories
2013/14 Conjunction Class
C_3 (Departure Energy) km^2/sec^2



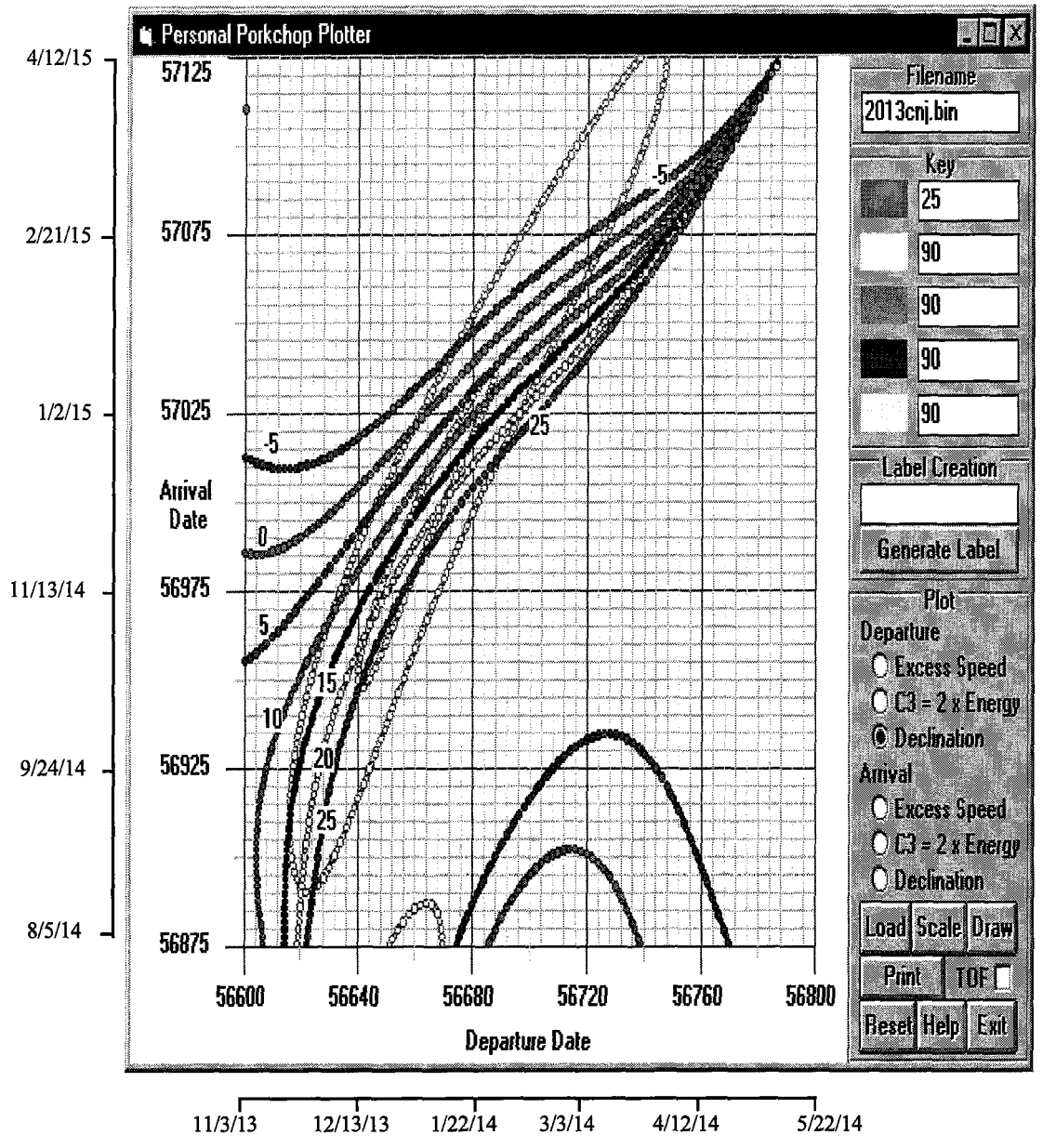
Earth-Mars Trajectories
2013/14 Cargo Missions
Departure Excess Speed (km/sec)



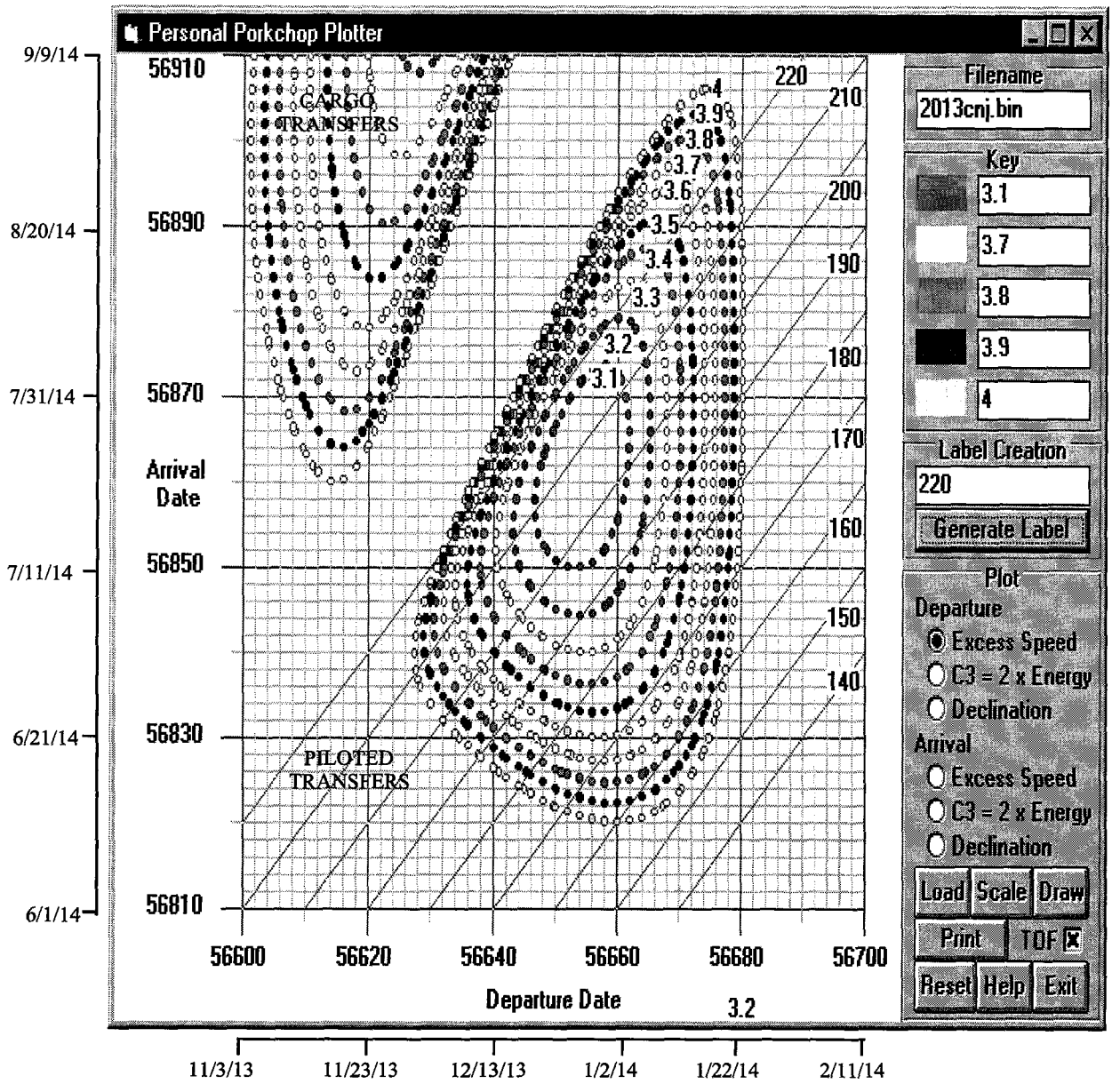
Earth-Mars Trajectories
2013/14 Cargo Missions
C_3 (Departure Energy) km^2/sec^2



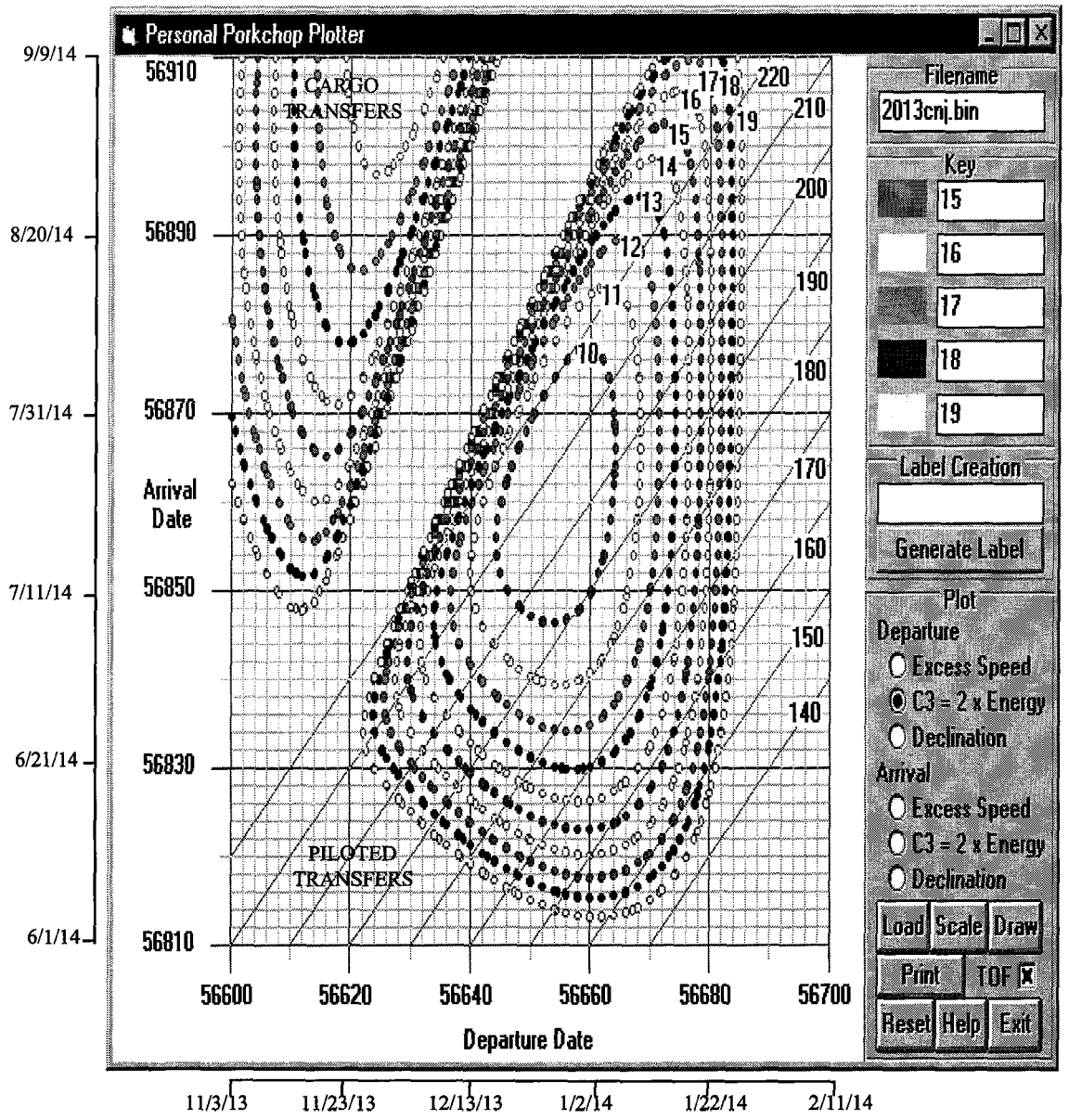
Earth-Mars Trajectories
2013/14 Cargo Missions
Departure Declination (Degrees)



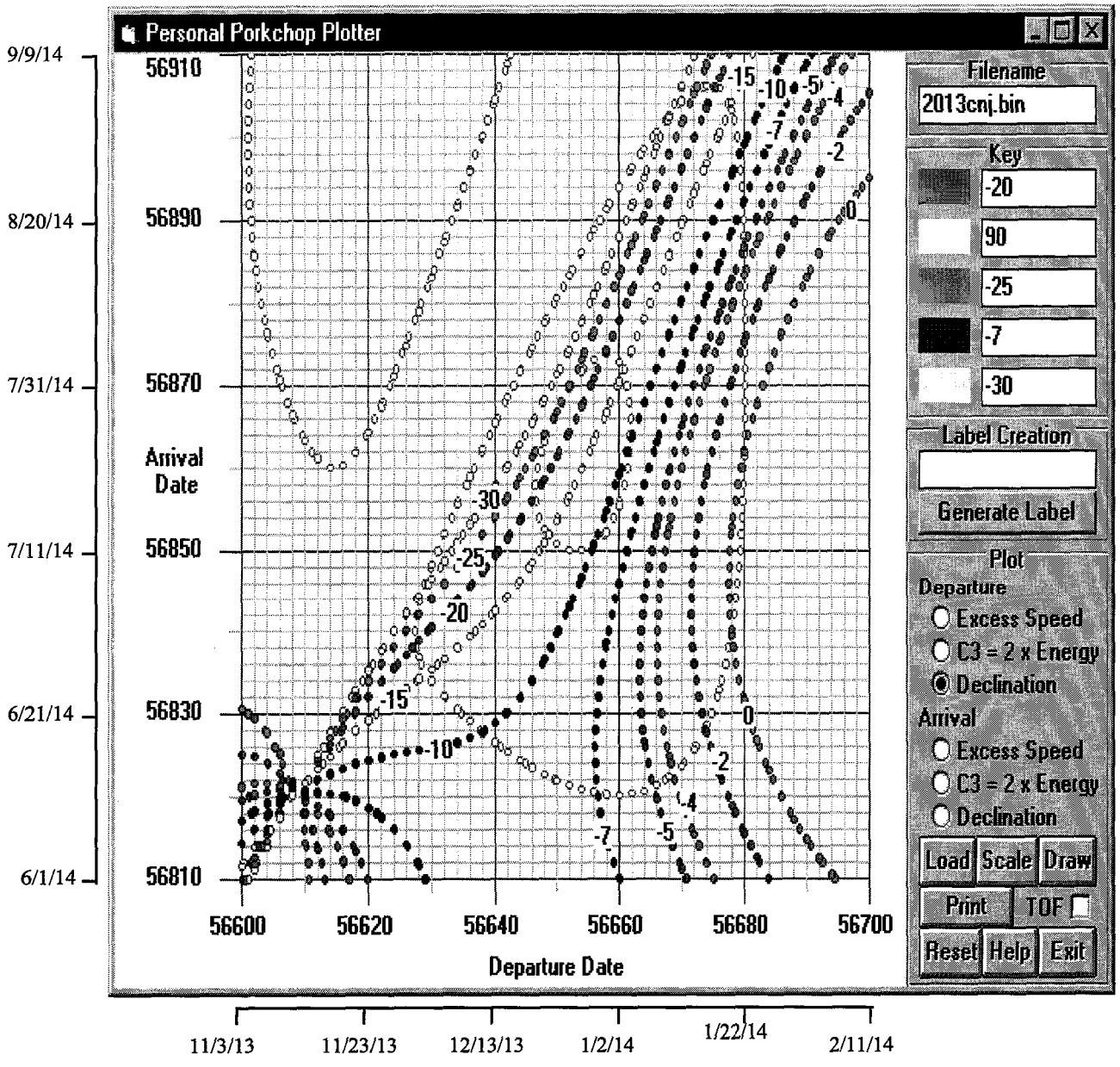
Earth-Mars Trajectories
2013/14 Piloted Missions
Departure Excess Speed (km/sec)



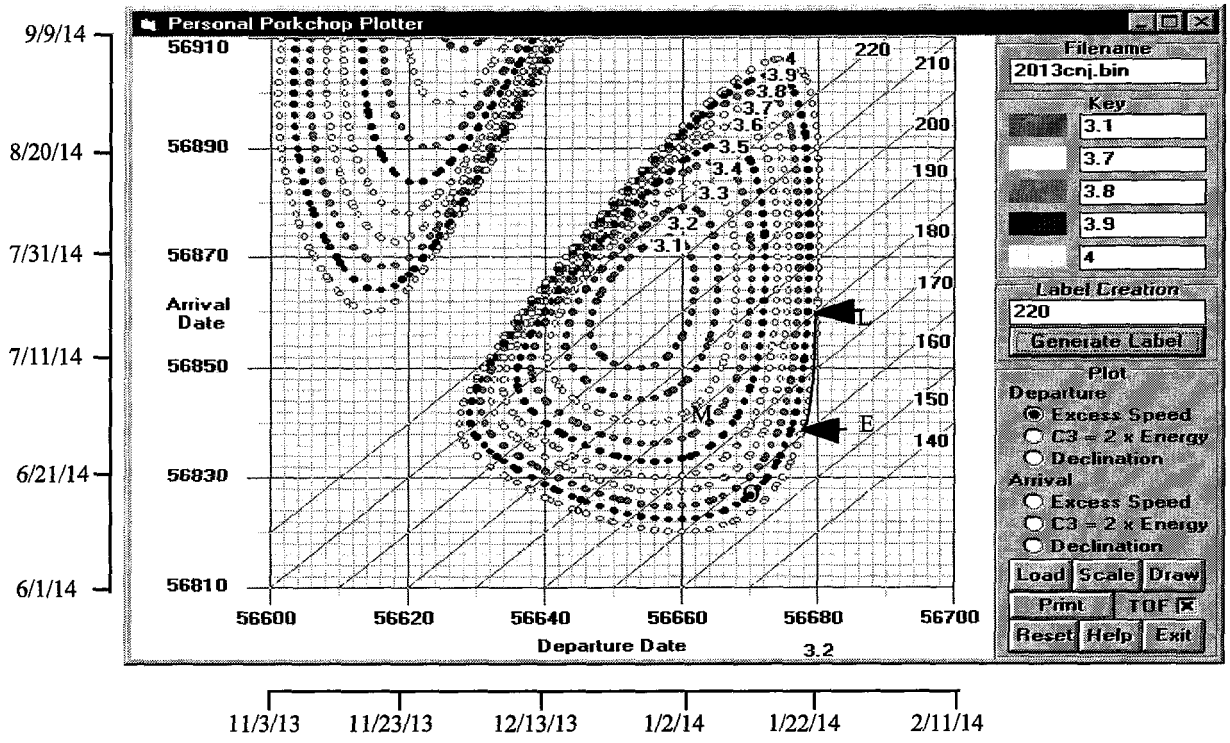
Earth-Mars Trajectories
2013/14 Piloted Missions
C_3 (Departure Energy) km^2/sec^2



Earth-Mars Trajectories
2013/14 Piloted Missions
Departure Declination (Degrees)



Earth-Mars Trajectories
2013/14 Piloted Missions
Baseline Mission Designed to
2011 Departure Excess Speed



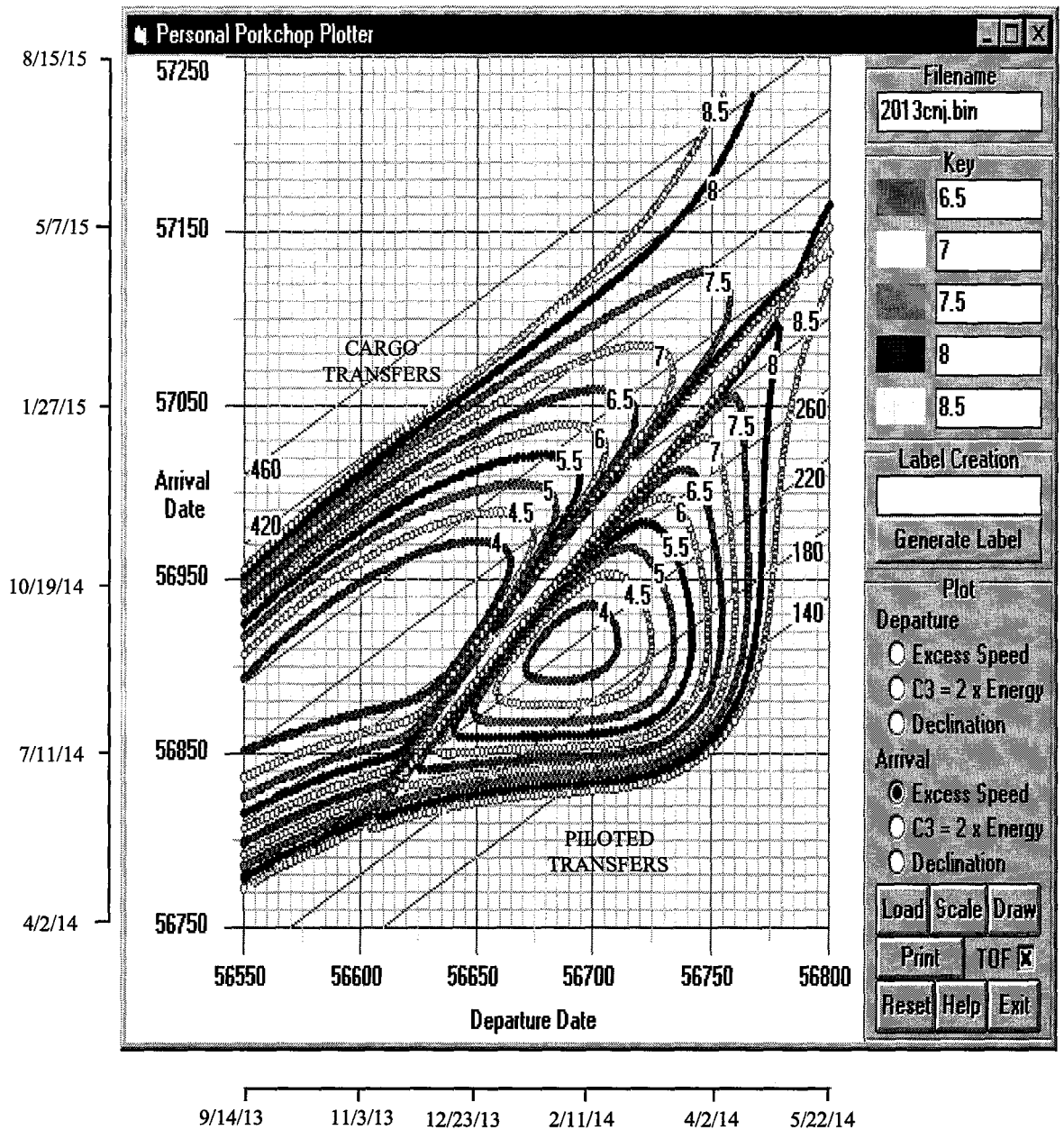
E=Minimum flight time trajectory using 2011 Piloted Mission Departure Excess Speed (3.99 km/sec) and while maintaining acceptable Mars entry velocity needed for aerobraking.
Departure: 1/20/14 (56678J) Arrival: 6/30/14 (56839J)

L=Latest possible trajectory to keep flight time limited to 180 days. The acceptable window of opportunity for launch will be along the arc from E to L.
Latest Departure: 1/22/14 (56679J) Arrival: 7/21/14 (56859J)

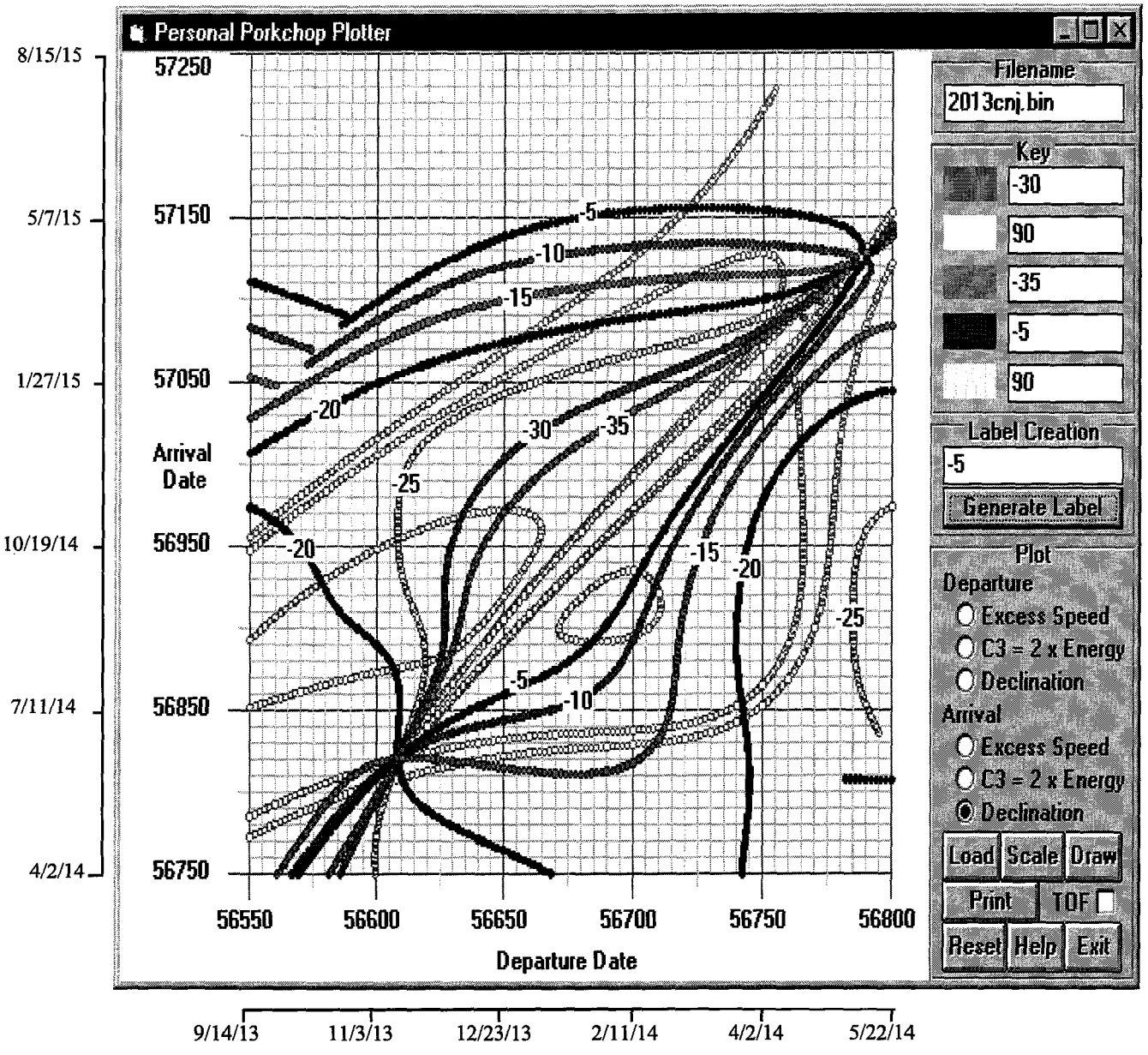
O=Minimum flight time trajectory using 2011 Piloted Mission Departure Excess Speed (3.99 km/sec). Mars arrival excess speed=8.56 km/sec, which exceeds the limit of 7.167 km/sec
Departure: 1/13/14 (56671J) Arrival: 6/16/14 (56825J)

M=Minimum departure excess speed and initial mass trajectory for 2014 opportunity for a flight time of 180 days.
Departure: 1/4/14 (56662J) Arrival: 7/3/14 (56842J)

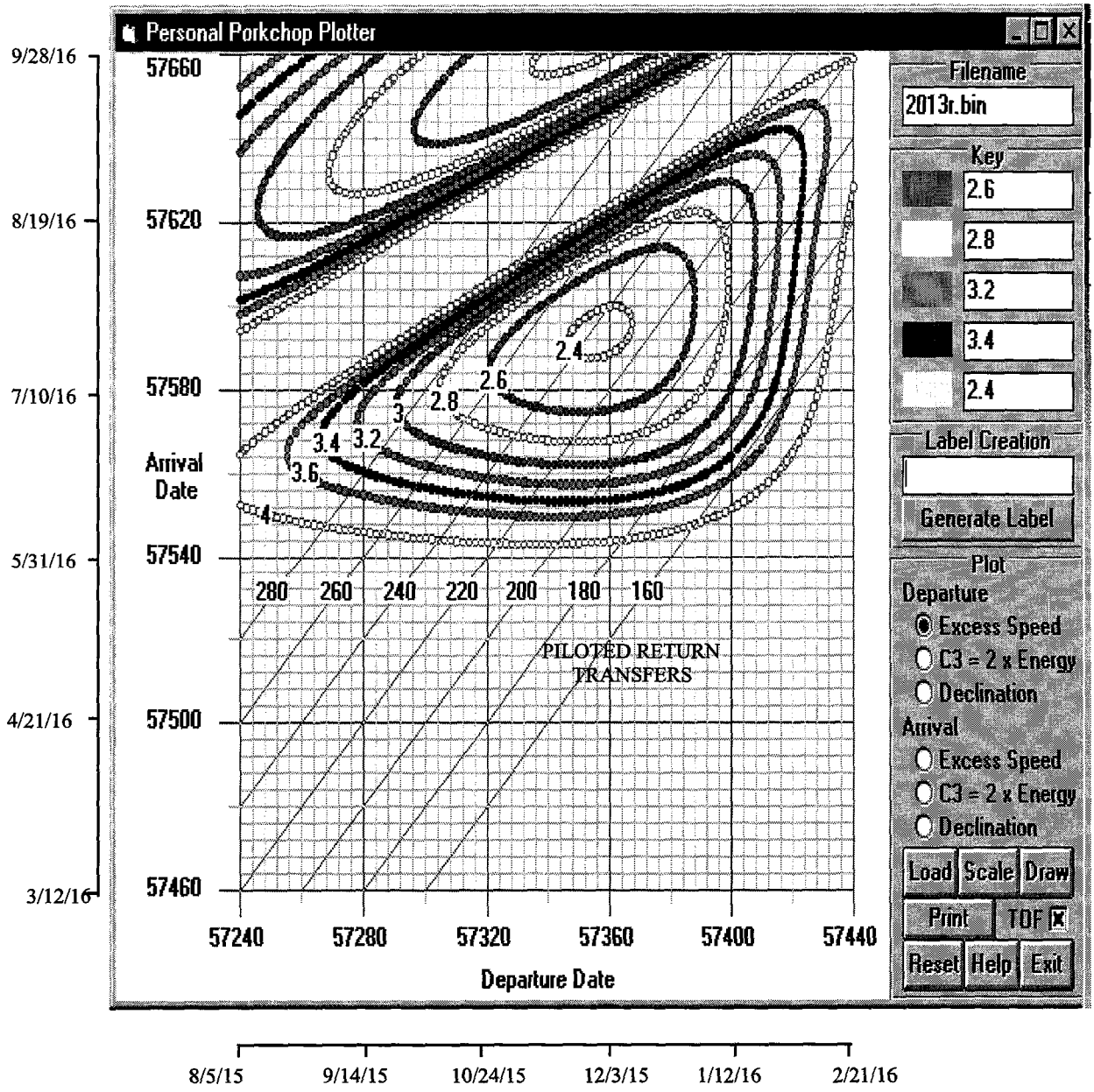
Earth-Mars Trajectories
2013/14 Conjunction Class
Arrival Excess Speed (km/sec)



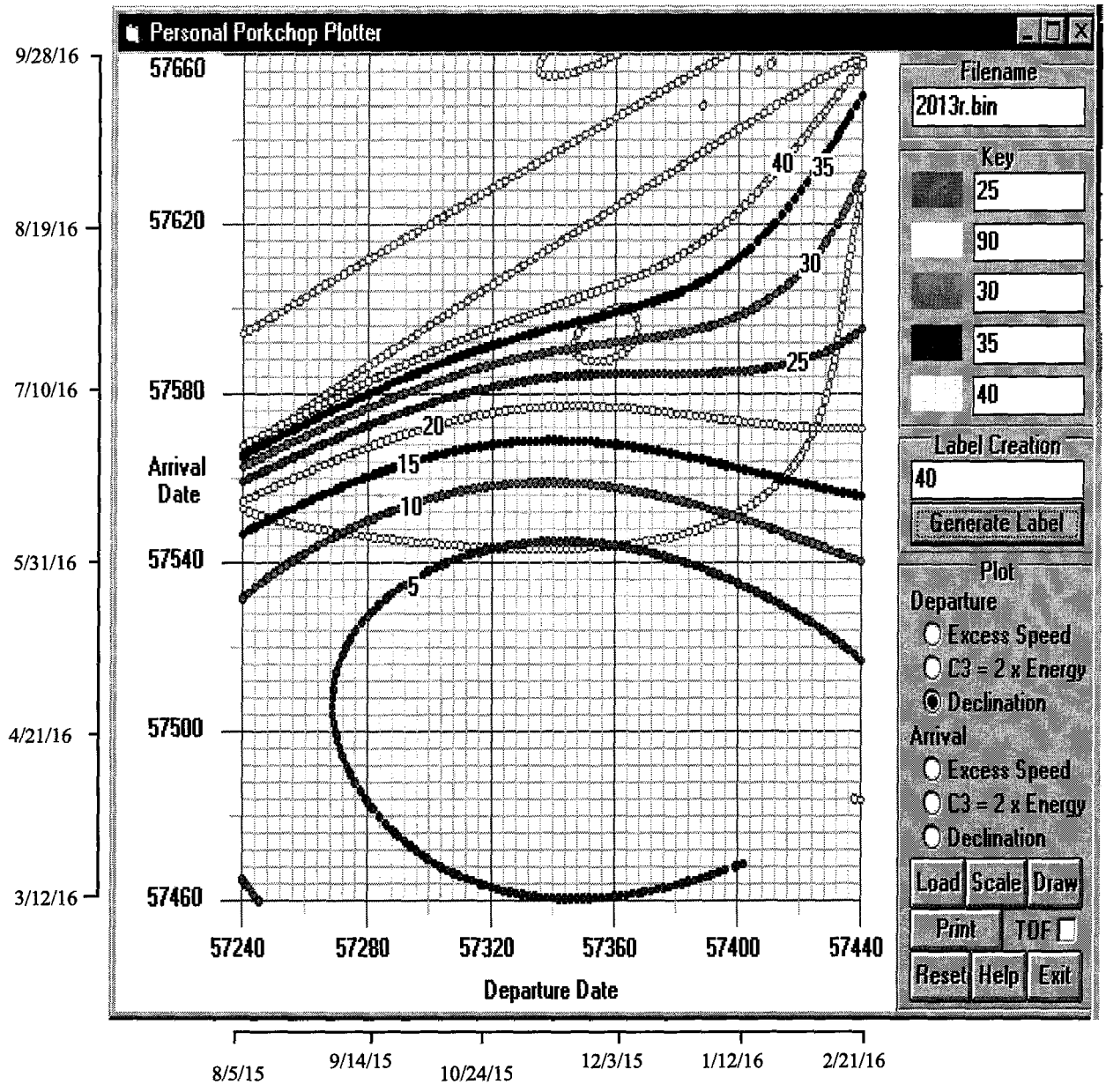
Earth-Mars Trajectories
2013/14 Conjunction Class
Arrival Declination (Degrees)



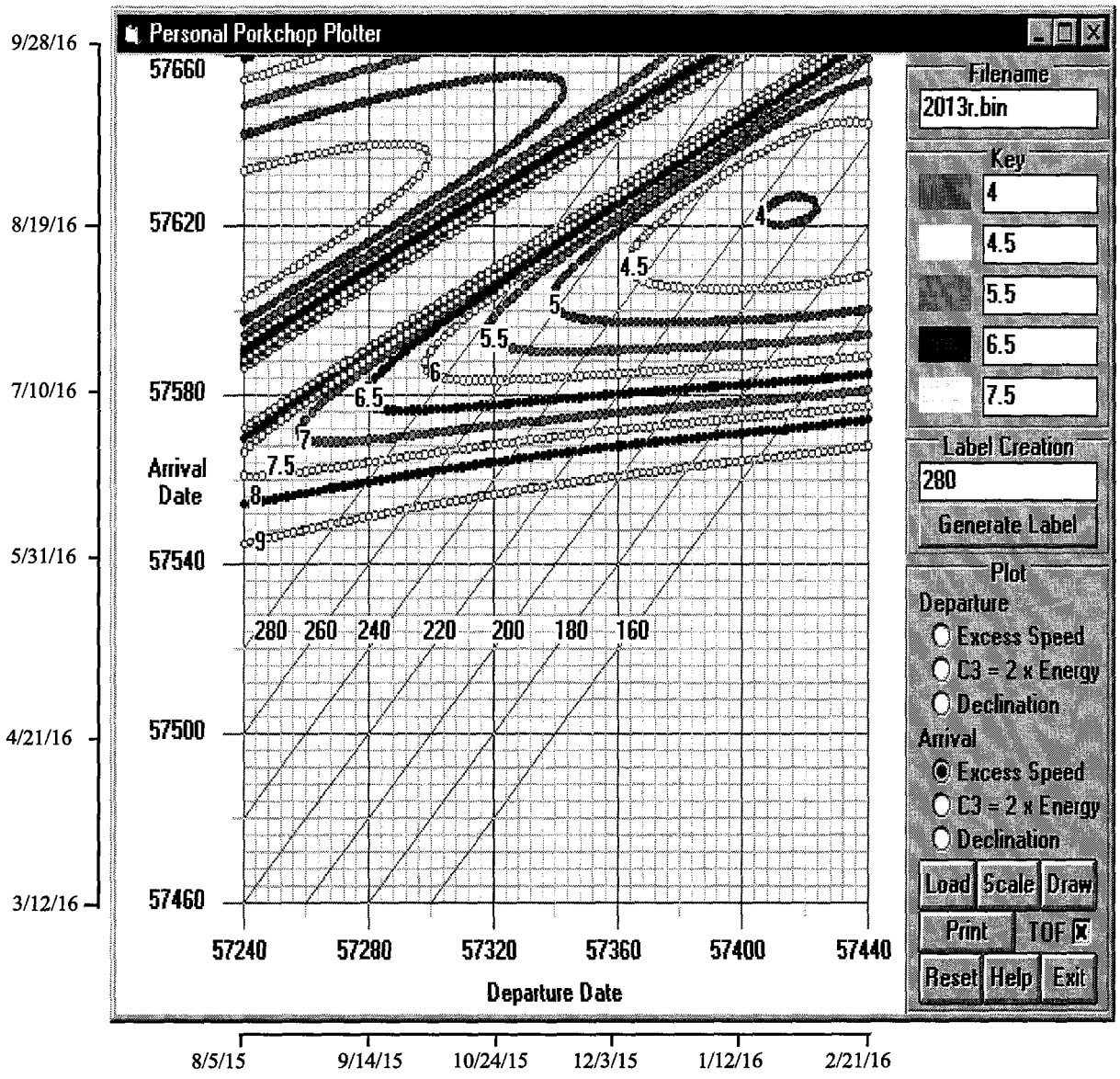
Mars-Earth Trajectories
2015/16 Conjunction Class
(Returns from 2013/14 Missions)
Departure Excess Speed (km/sec)



Mars-Earth Trajectories
2015/16 Conjunction Class
(Returns from 2013/14 Missions)
Departure Declination (Degrees)



Mars-Earth Trajectories
2015/16 Conjunction Class
(Returns from 2013/14 Missions)
Arrival Excess Speed (Degrees)



Mars-Earth Trajectories
2015/16 Conjunction Class
(Returns from 2013/14 Missions)
Arrival Declination (Degrees)

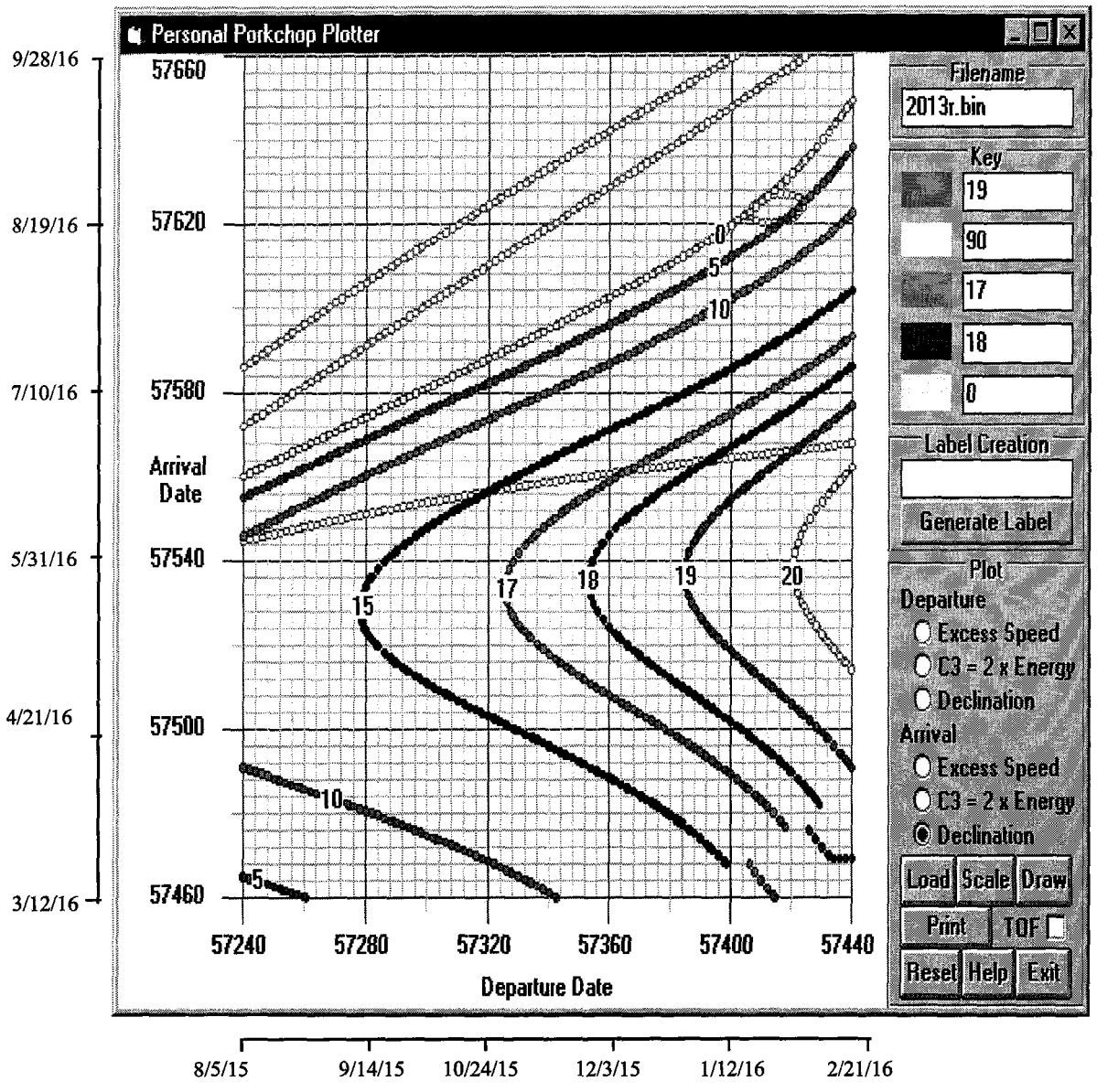


Table 12. 2016 opportunities summary.

Mission Type	TMI Date (m/d/yr)	TMI ΔV (m/sec)	Velocity Losses (m/sec)	Mars Arrival Date (m/d/yr)	Outbound Flight Time (days)	Mars Stay Time (days)	Mars Departure Date (m/d/yr)	TEI ΔV (m/sec)	Return Time (days)	Return Date (m/d/yr)	Total Mission Duration (days)	C_3 (km^2/sec^2)	Total ΔV (m/sec)	Depart. V_∞@ Earth (km/sec)	Arrival V_∞@ Mars (km/sec)	Arrival Velocity @ Mars (km/sec)	Depart. V_∞@ Mars (km/sec)	Arrival V_∞@ Earth (km/sec)	Arrival Velocity @ Earth (km/sec)
Piloted[1]	2/20/16	3,677	99	8/19/16	181	583	3/25/18	898	180	9/21/18	944	8.87	4,575	2.979	5.297	7.237	2.642	4.012	11.776
Cargo 1	3/21/16	3,627	88	1/20/17	305	—	—	—	—	—	—	7.99	3,627	2.827	5.368	7.289	—	—	—
Cargo 2	3/21/16	3,647	109	1/20/17	305	—	—	—	—	—	—	7.99	3,647	2.827	5.368	7.289	—	—	—
Piloted	3/14/16	4,019	132	7/29/16	137	630	4/20/18	1,476	130	8/28/18	897	15.92	5,495	3.989	7.167	8.700	3.688	8.910	14.212
Piloted[2]	3/7/16	4,019	132	7/14/16	129	645	4/20/18	1,476	130	8/28/18	904	15.92	5,495	3.989	8.769	10.060	3.688	6.760	8.367
Piloted[3]	3/21/16	4,019	132	9/17/16	180	610	5/20/18	1,476	180	11/16/18	970	15.92	5,495	3.989	3.965	6.328	3.688	4.105	6.416

1) Optimal piloted trajectory (minimum initial mass)

2) Entry Velocity Limit of 8.7 km/sec at Mars exceeded

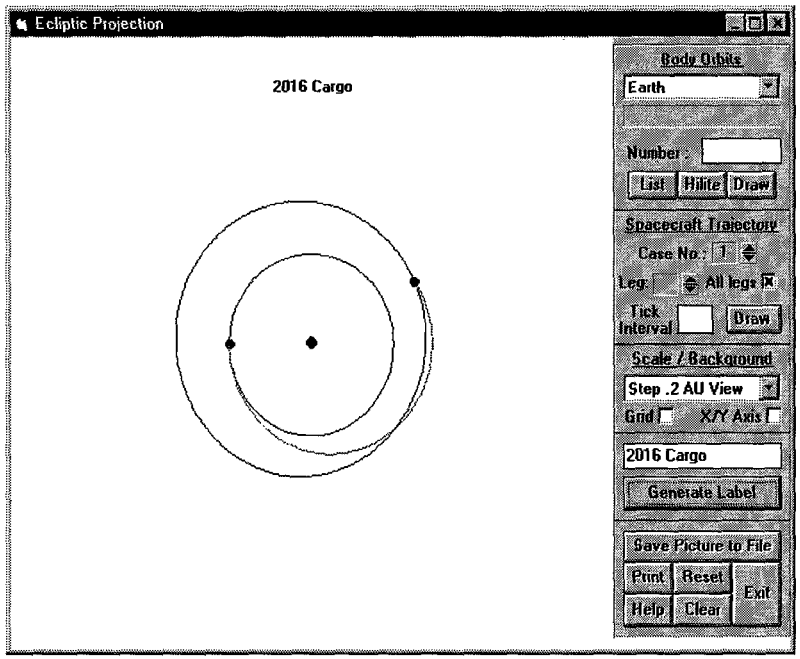
3) Latest possible launches designed to 2011/180 day C_3s

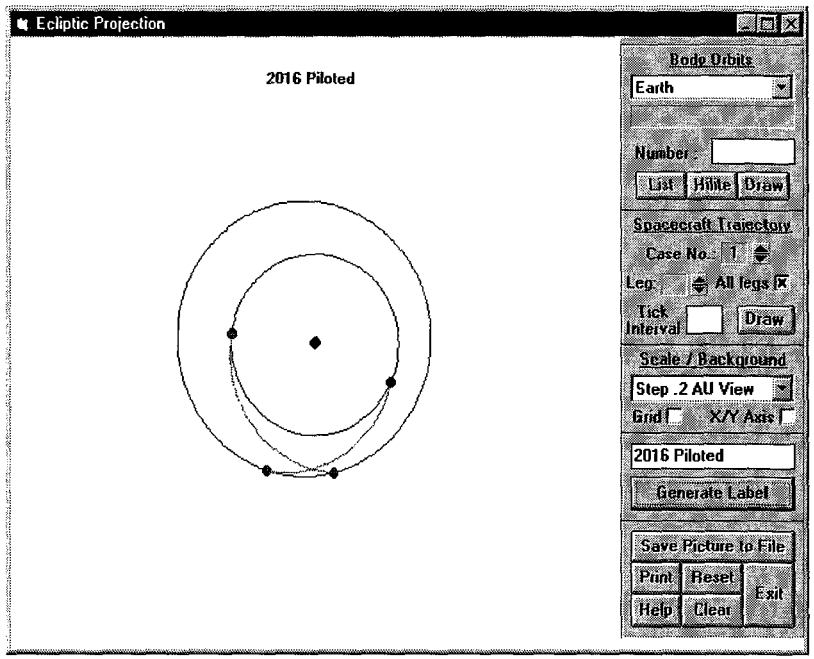
8-day Earth-Mars Departure Window:

Depart:	TOF	Arrival:
3/14/16	137	7/29/16
3/21/16	180	9/17/16

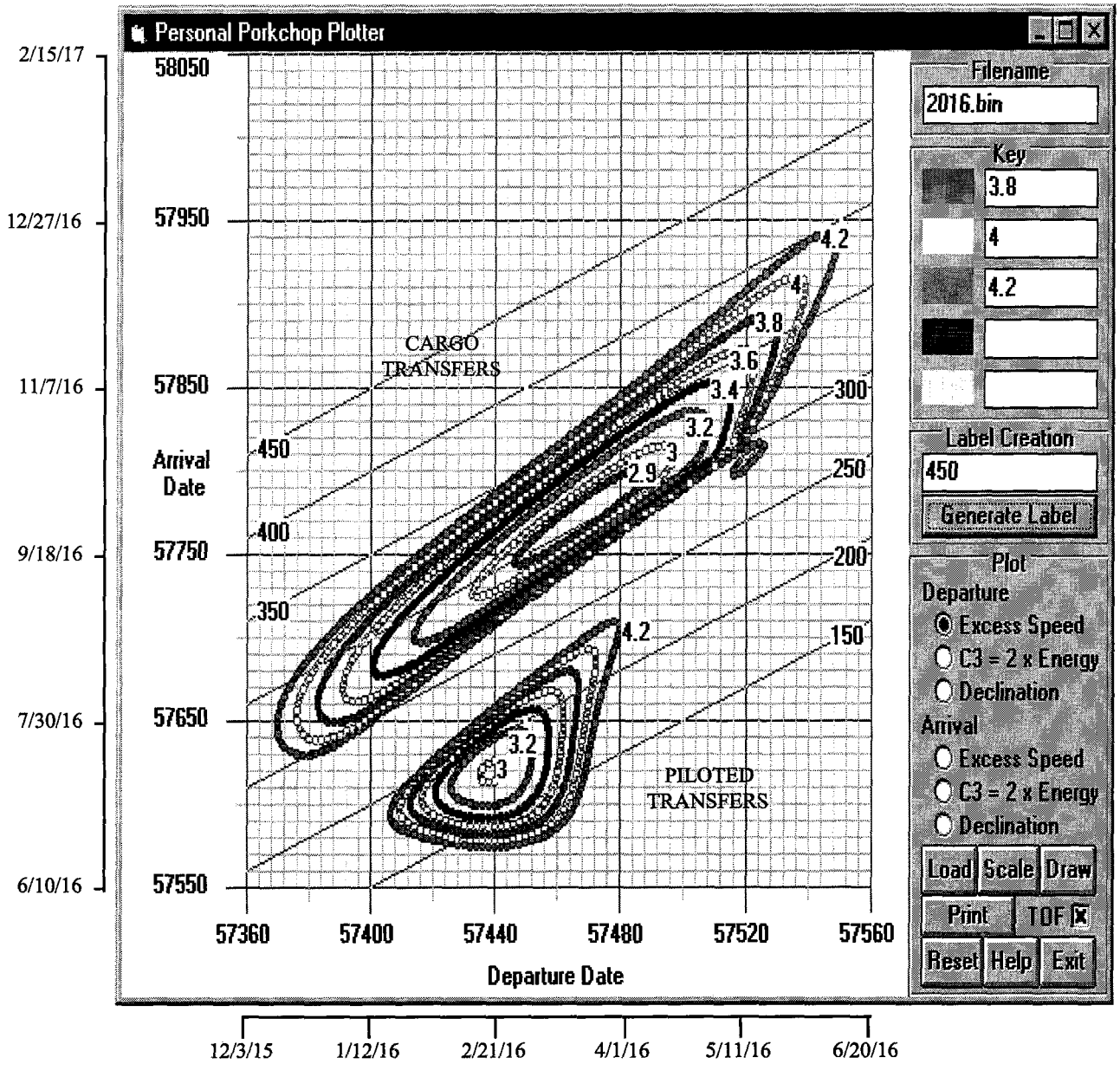
30-day Mars-Earth Return Window:

Depart:	TOF	Arrival:
4/20/18	130	8/28/18
5/20/18	180	11/16/18

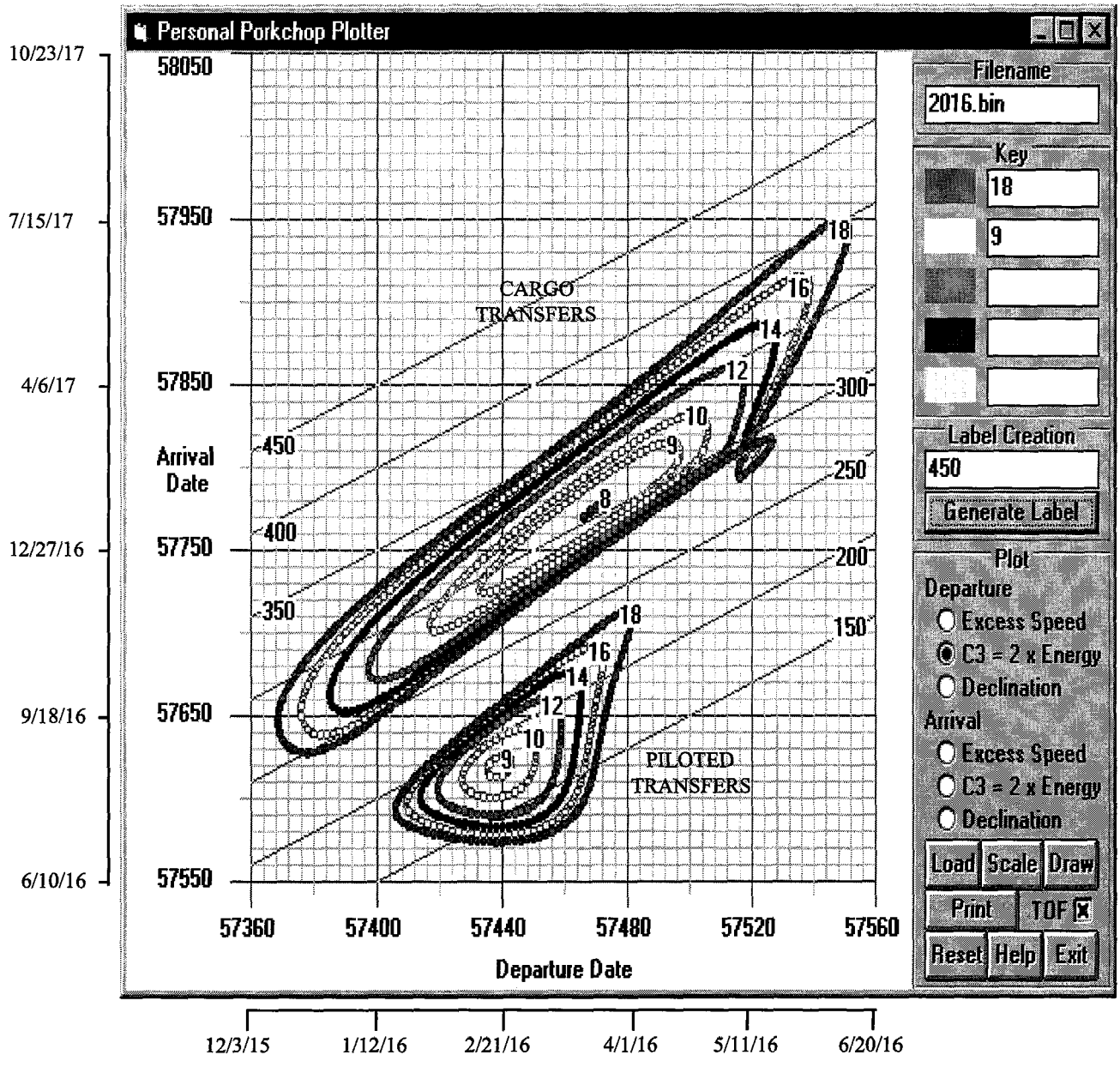




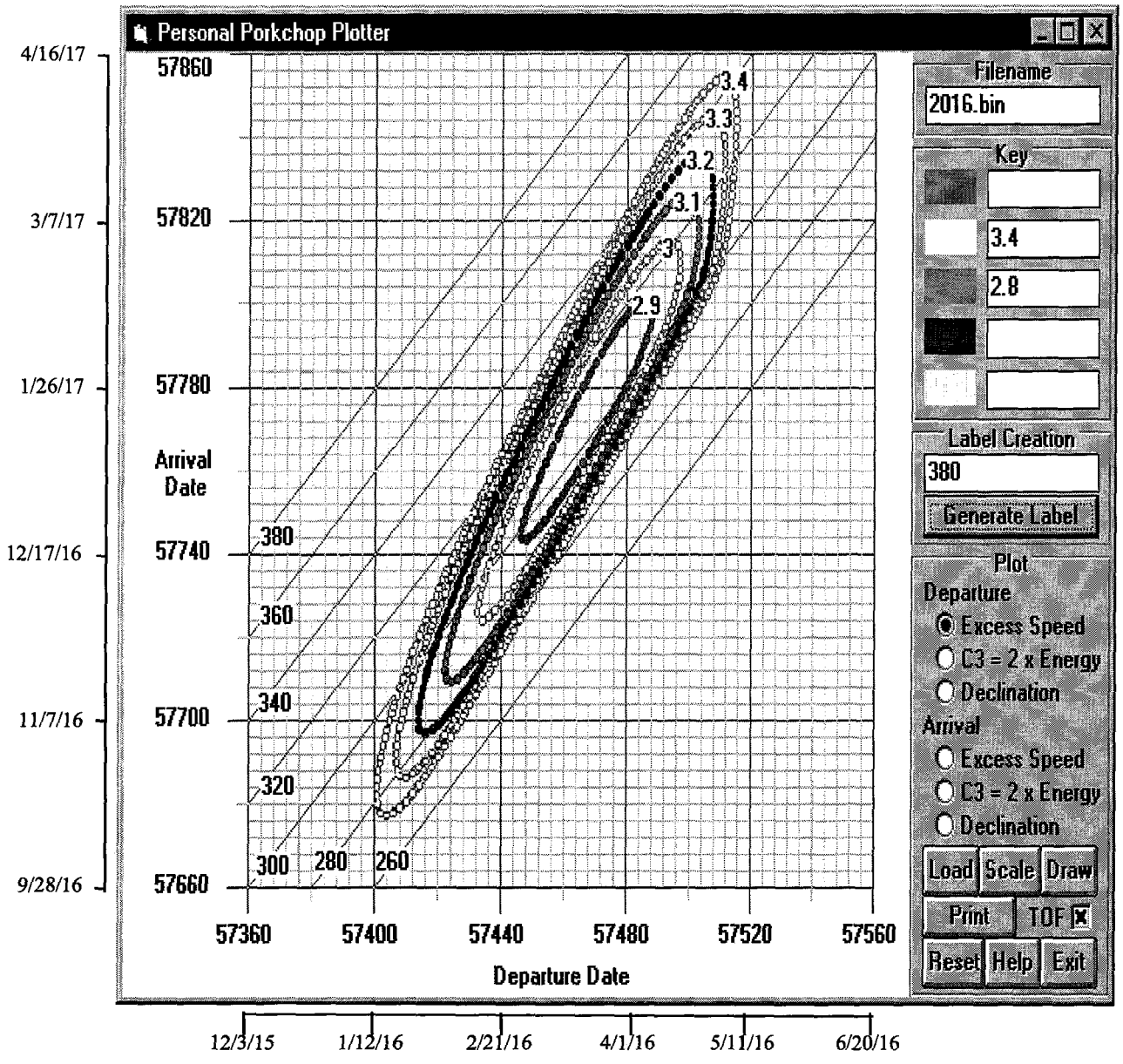
Earth-Mars Trajectories
2016 Conjunction Class
Departure Excess Speed (km/sec)



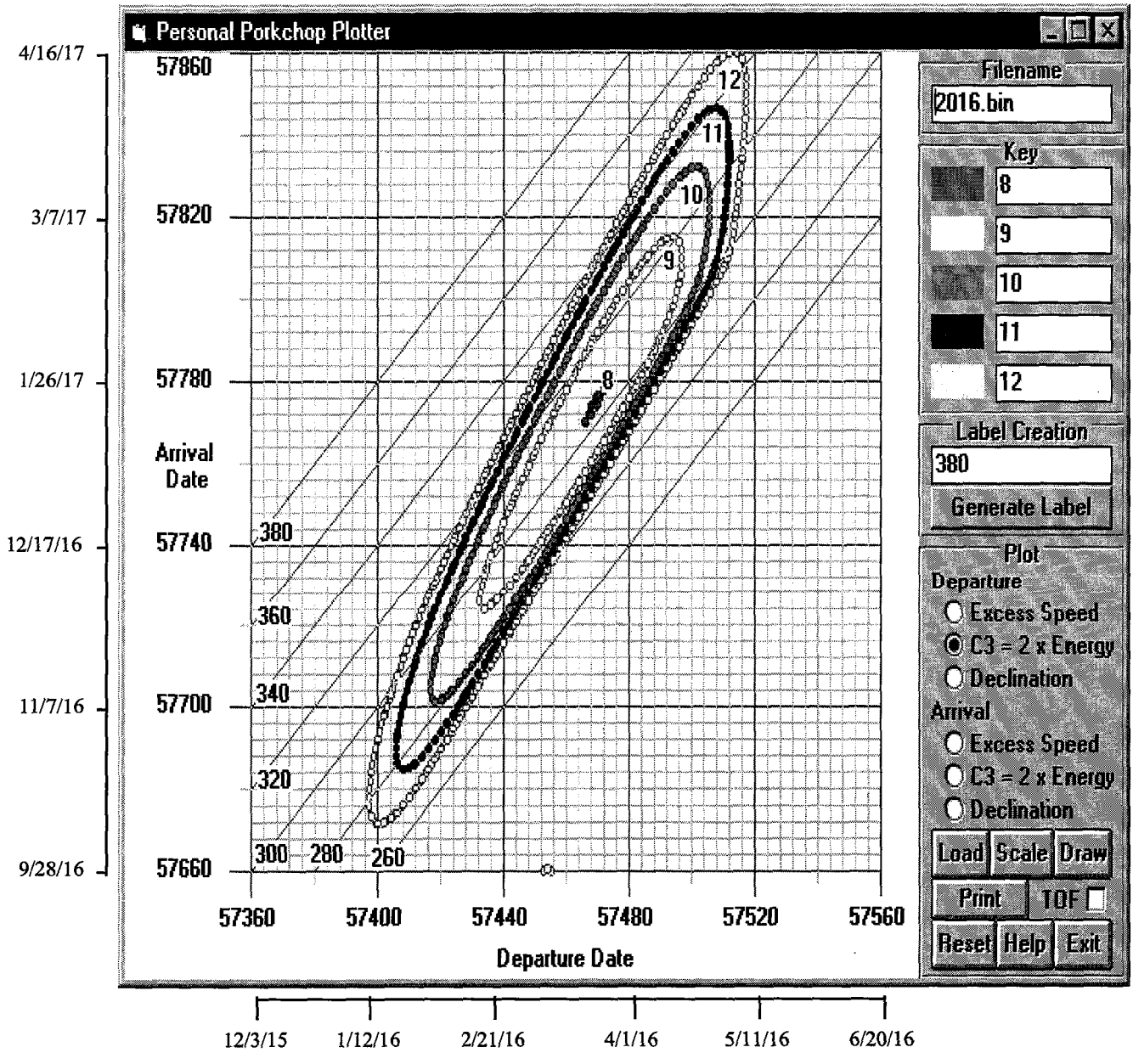
Earth-Mars Trajectories
2016 Conjunction Class
C_3 Departure Energy (km^2/sec^2)



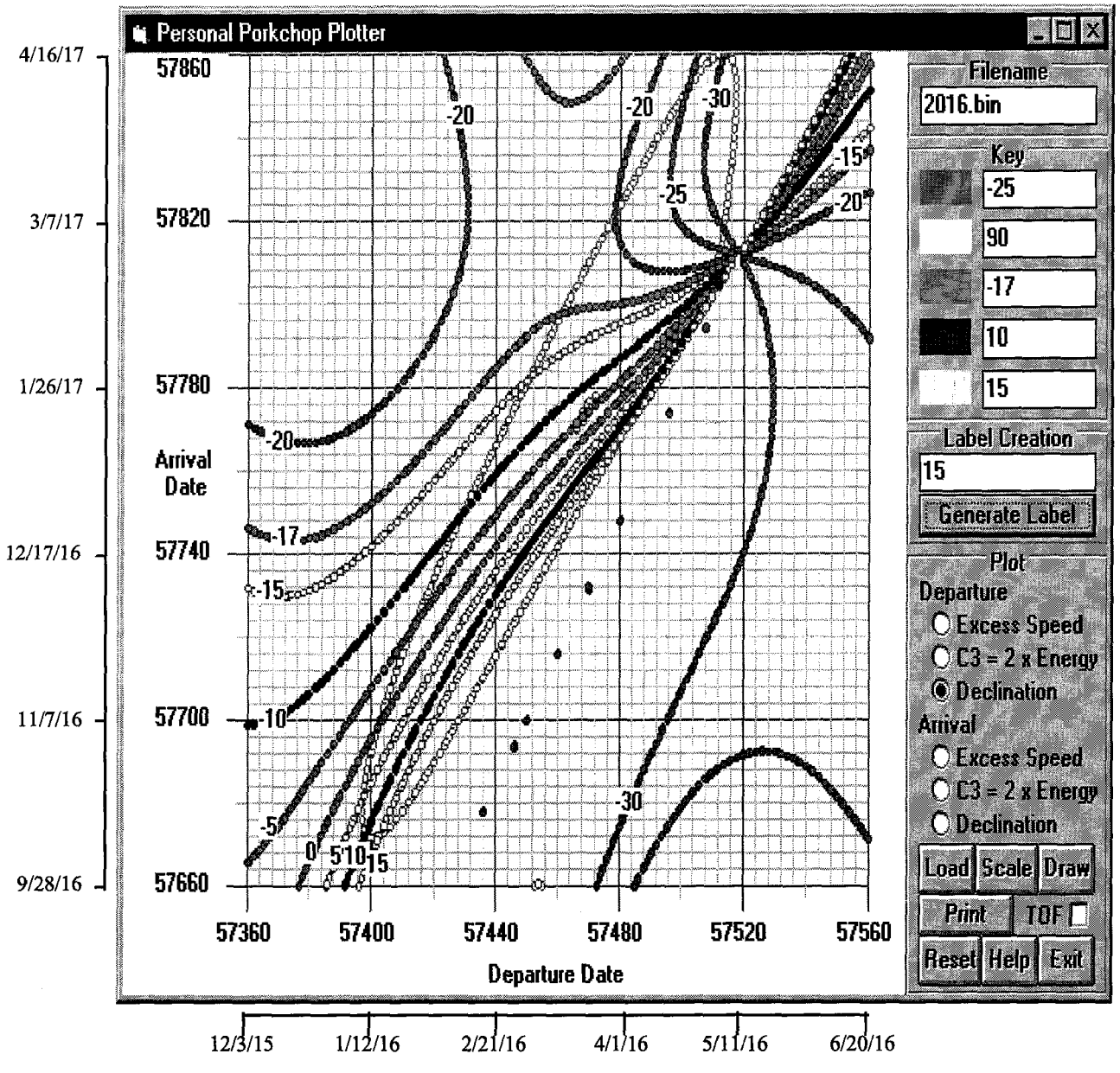
Earth-Mars Trajectories
2016 Cargo Missions
Departure Excess Speed (km/sec)



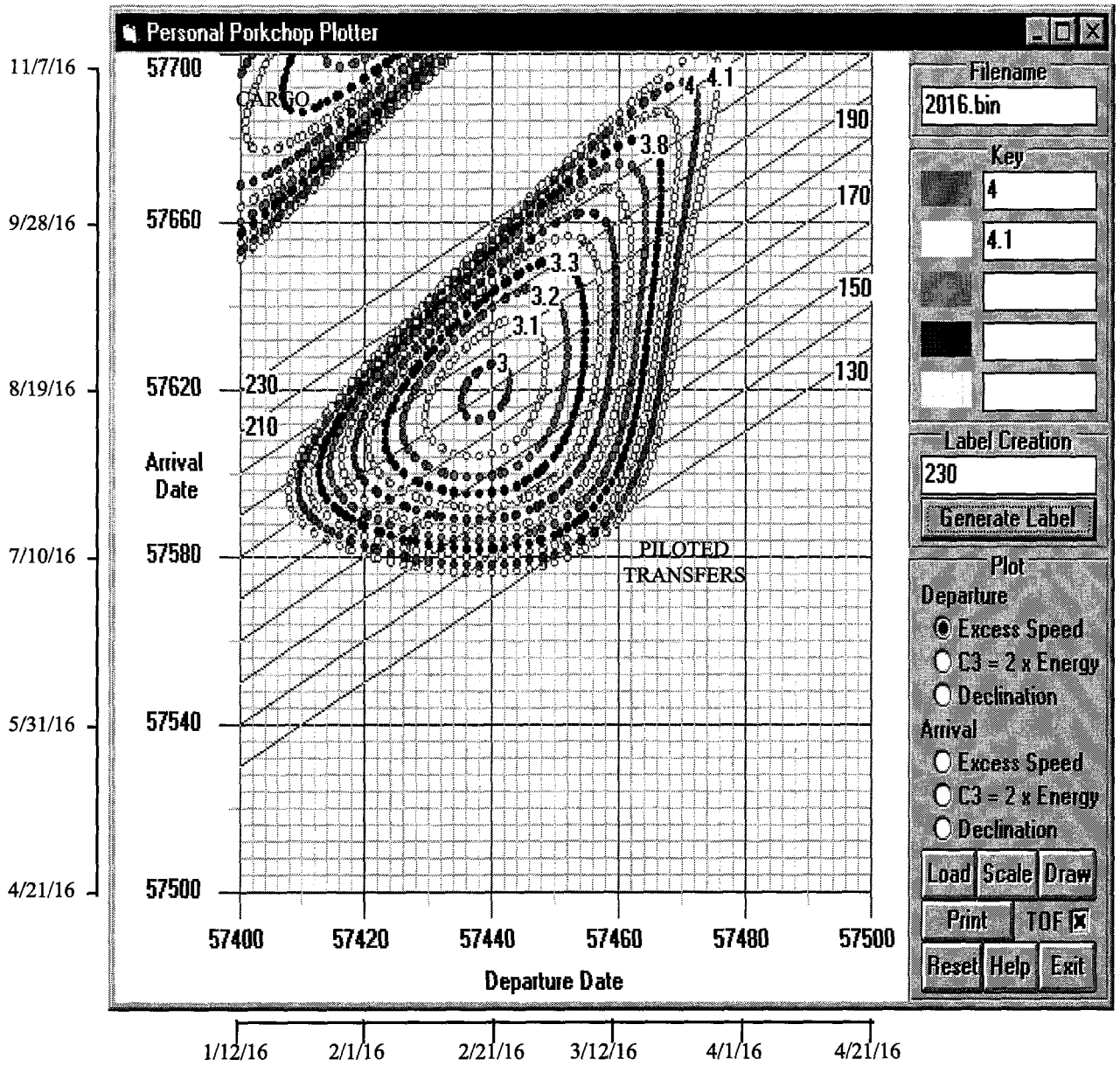
Earth-Mars Trajectories
2016 Cargo Missions
C_3 Departure Energy (km^2/sec^2)



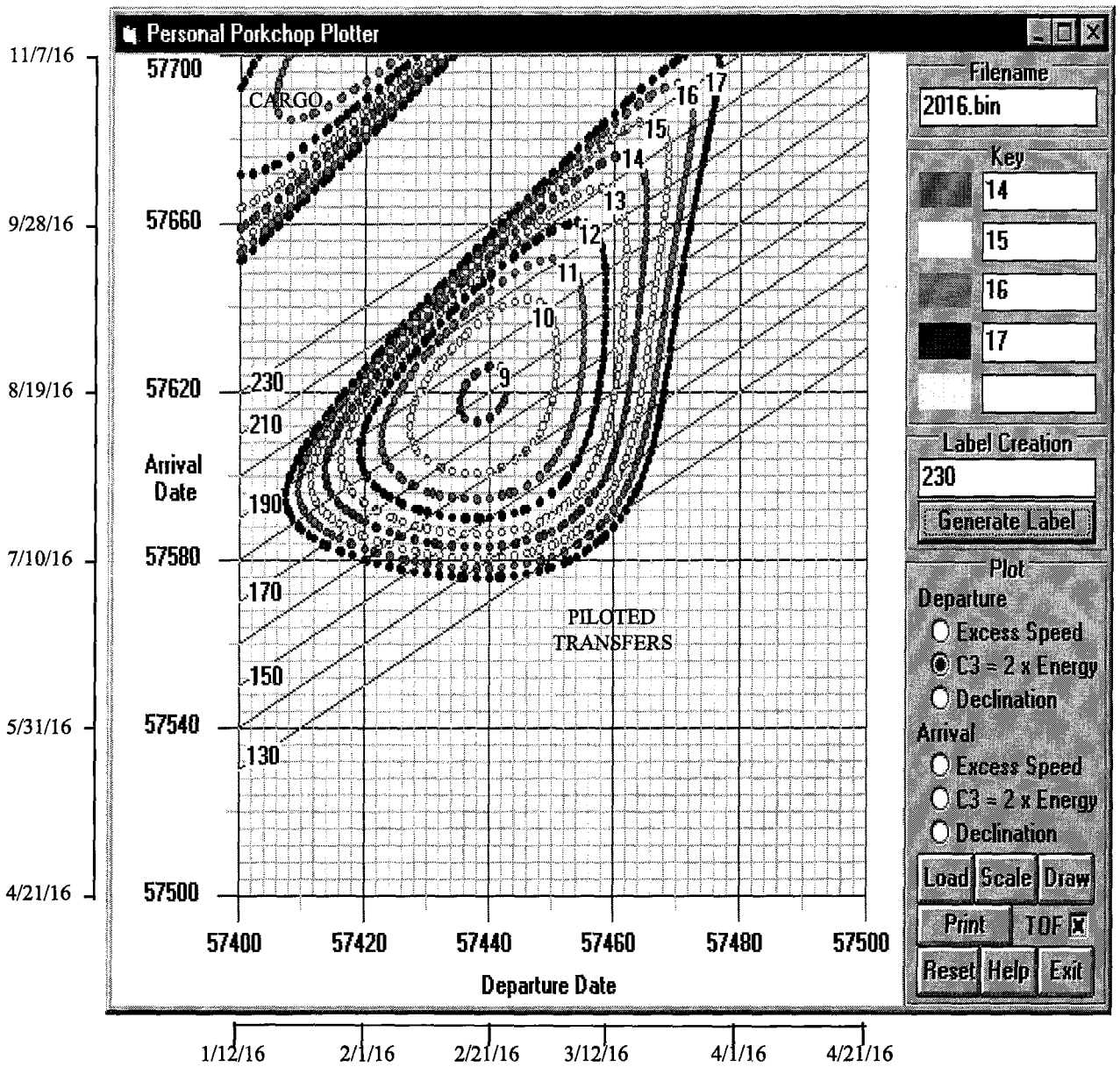
Earth-Mars Trajectories
2016 Cargo Missions
Departure Declination (Degrees)



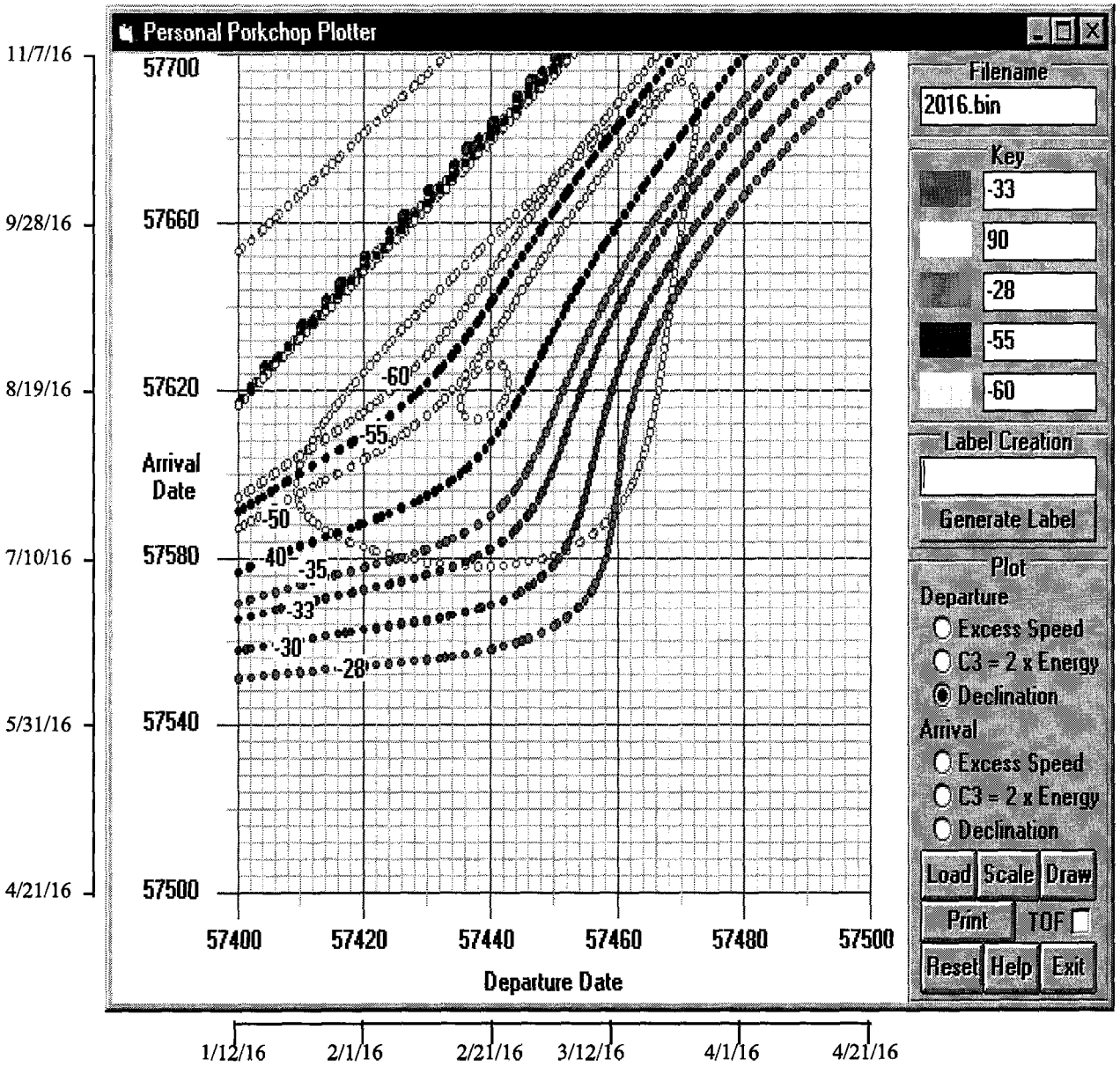
Earth-Mars Trajectories
2016 Piloted Missions
Departure Excess Speed (km/sec)



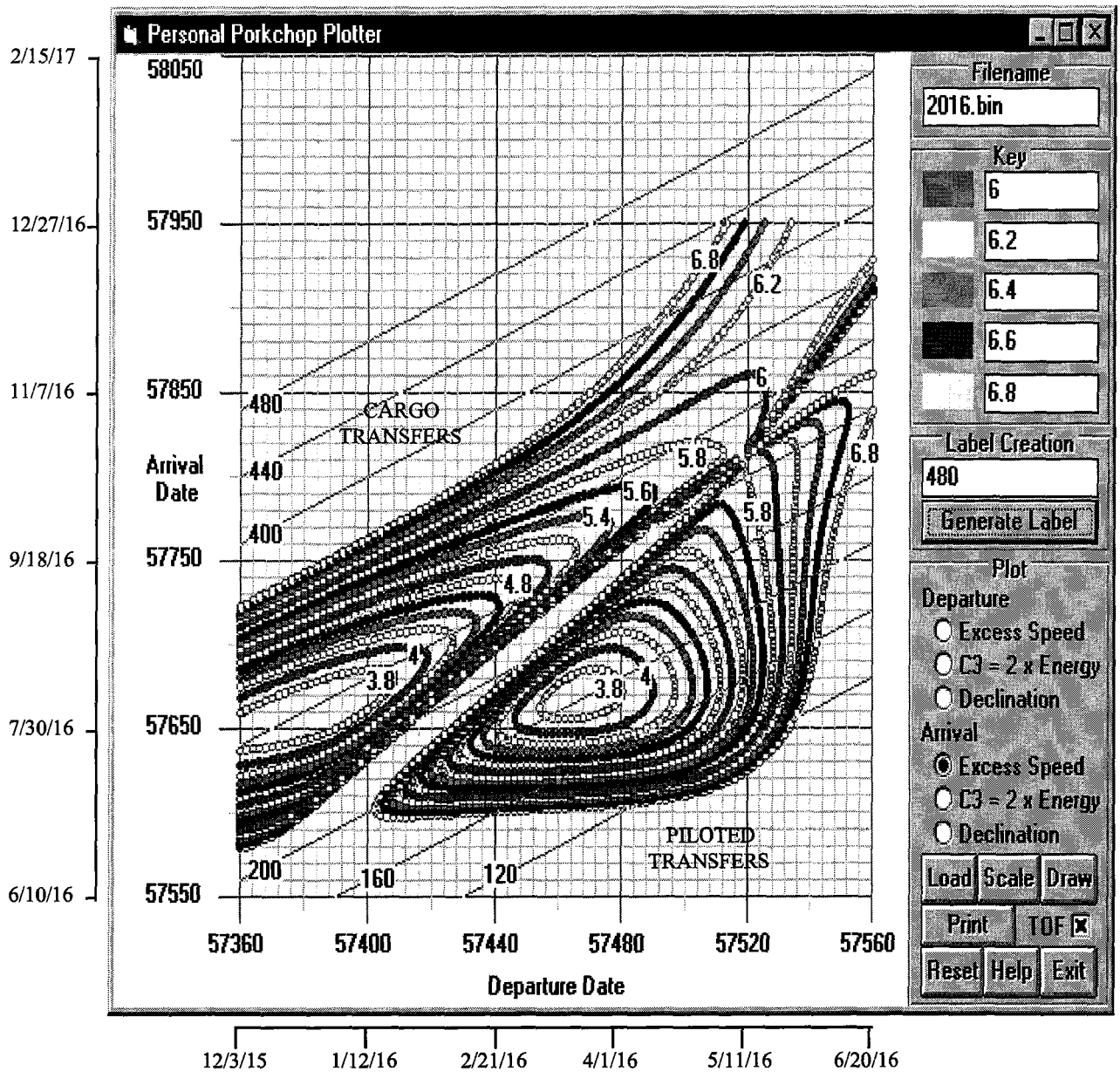
Earth-Mars Trajectories
2016 Piloted Missions
C_3 Departure Energy (km^2/sec^2)



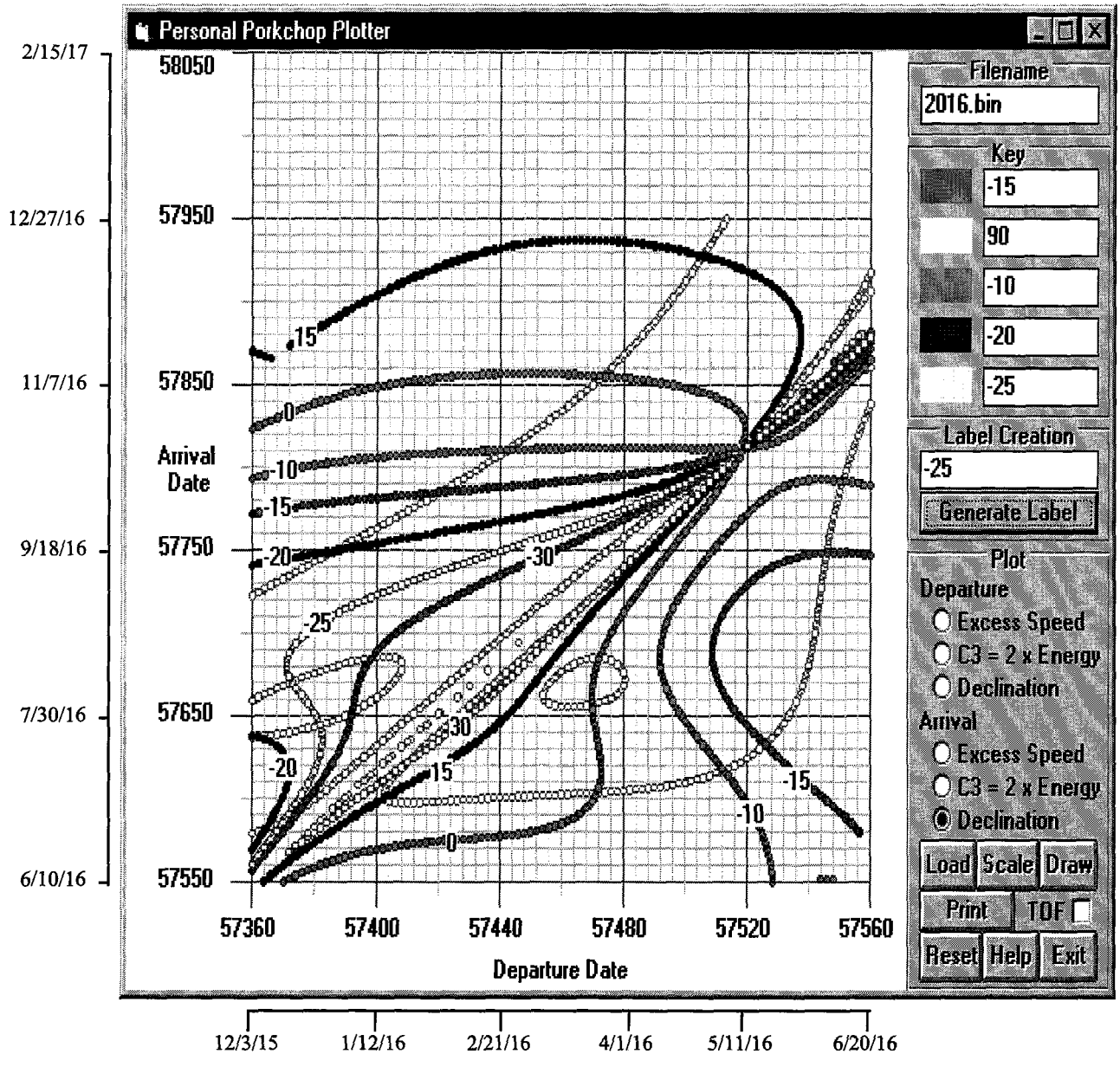
Earth-Mars Trajectories
2016 Piloted Missions
Departure Declination (Degrees)



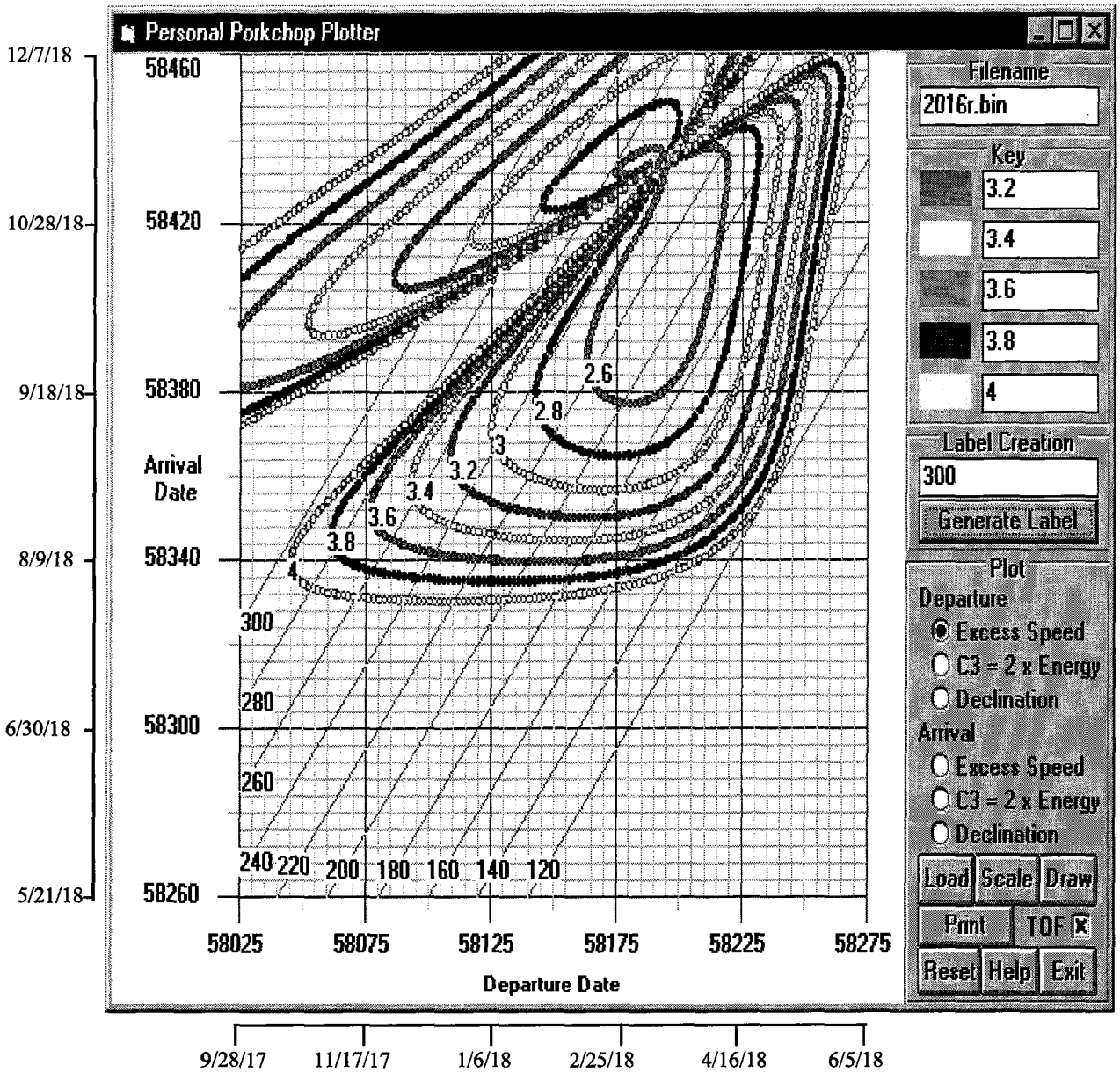
Earth-Mars Trajectories
2016 Conjunction Class
Arrival Excess Speed (km/sec)



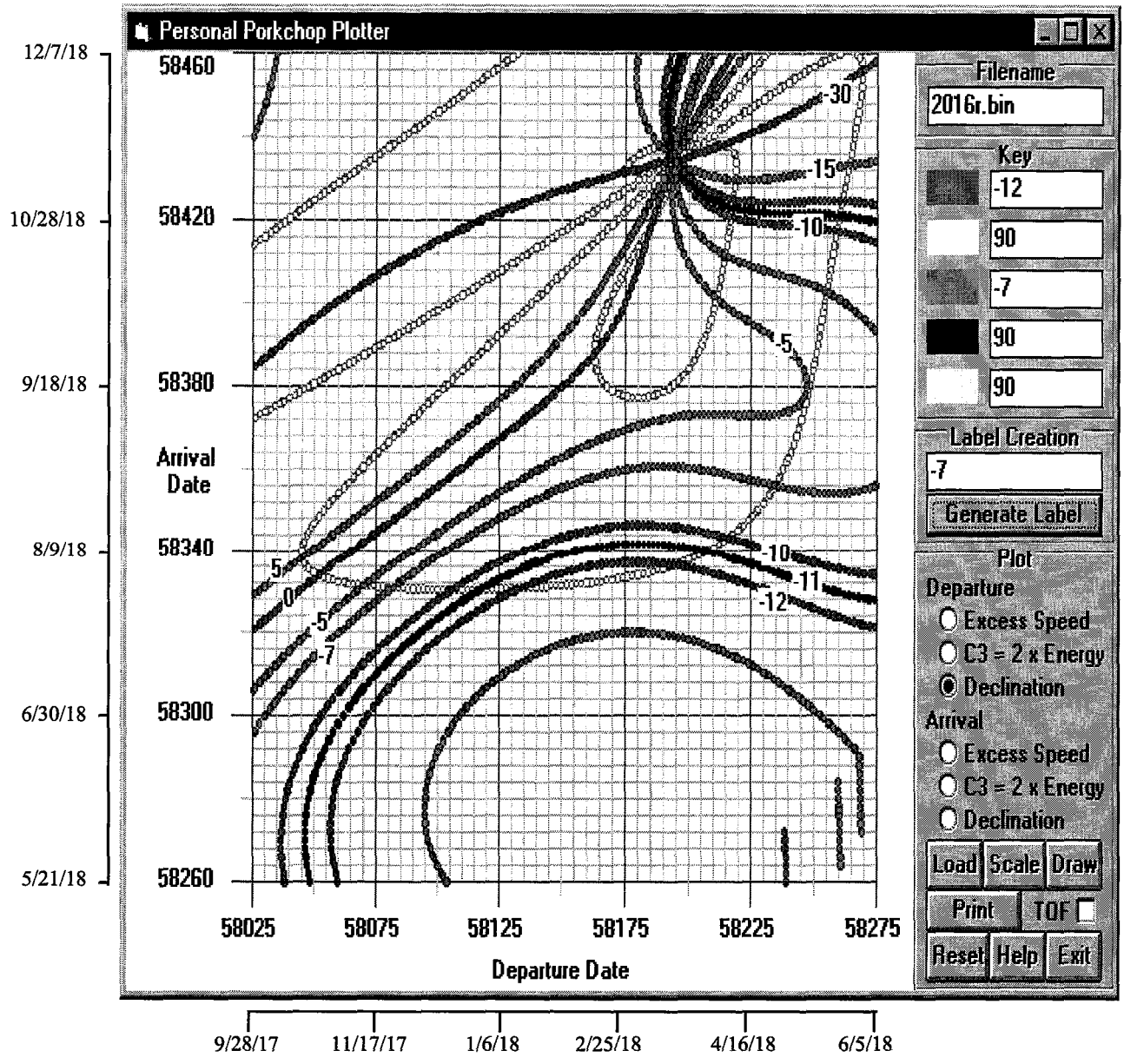
Earth-Mars Trajectories
2016 Conjunction Class
Arrival Declination (Degrees)



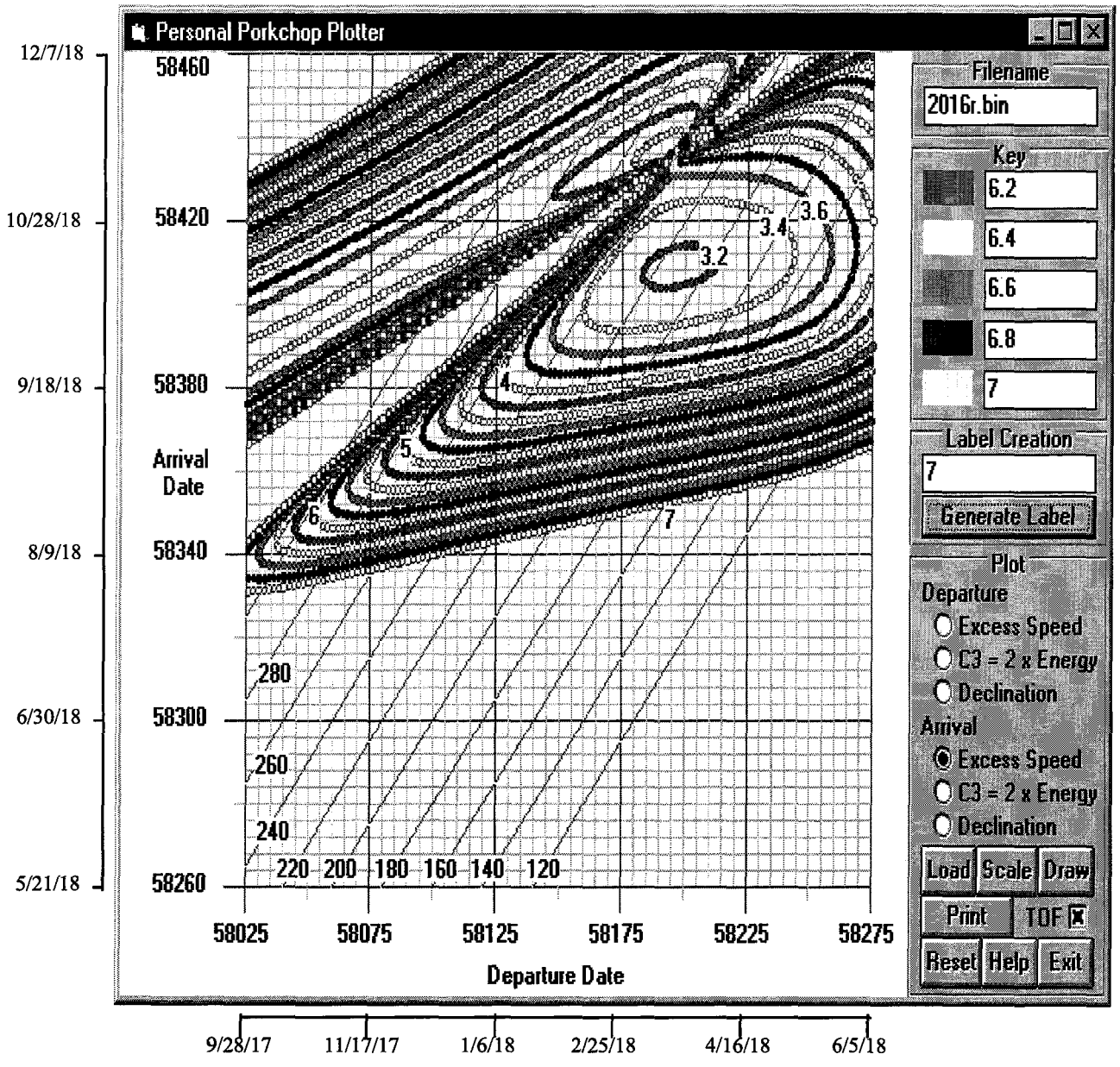
Mars-Earth Trajectories
2018 Conjunction Class
(Returns from 2016 Missions)
Departure Excess Speed (km/sec)



Mars-Earth Trajectories
2018 Conjunction Class
(Returns from 2016 Missions)
Departure Declination (Degrees)



Mars-Earth Trajectories
2018 Conjunction Class
(Returns from 2016 Missions)
Arrival Excess Speed (km/sec)



Mars-Earth Trajectories
2018 Conjunction Class
(Returns from 2016 Missions)
Arrival Declination (Degrees)

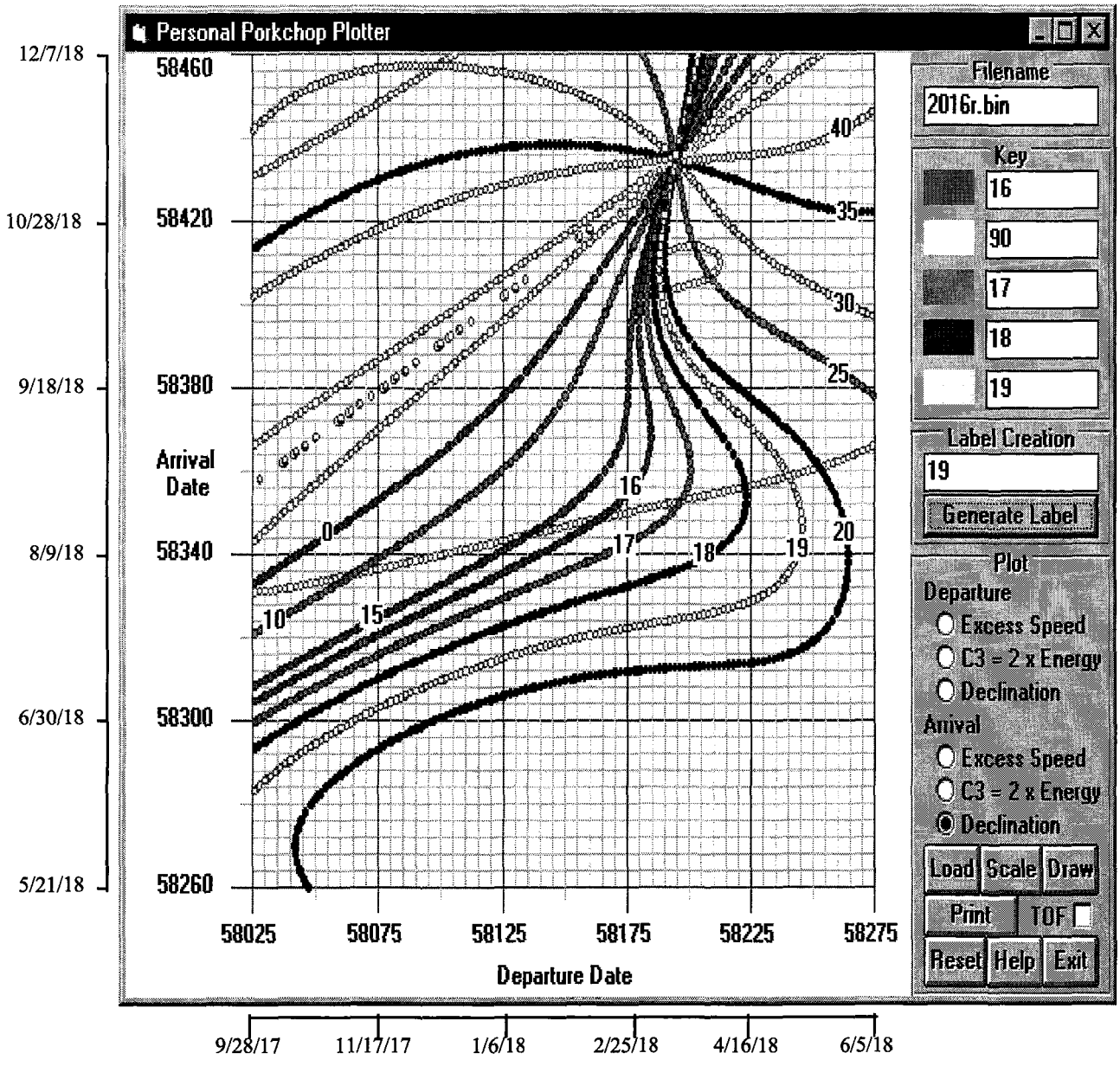


Table 13. 2018 opportunities summary.

Mission Type	TMI Date (m/d/yr)	TMI ΔV (m/s)	Velocity Losses (m/s)	Mars Arrival Date (m/d/yr)	Outbd Flight Time (days)	Mars Stay Time (days)	Mars Departure Date (m/d/yr)	TEI ΔV (m/sec)	Return Time (days)	Return Date (m/d/yr)	Total Mission Duration (days)	C_3 (km^2/sec^2)	Total ΔV (m/sec)	Depart. V_∞ @ Earth (km/sec)	Arrival V_∞ @ Mars (km/sec)	Arrival Velocity @ Mars (km/sec)	Depart. V_∞ @ Mars (km/sec)	Arrival V_∞ @ Earth (km/sec)	Arrival Velocity @ Earth (km/sec)
Piloted[1]	5/8/18	3,641	97	11/4/18	180	586	6/12/20	1,314	180	12/9/20	946	8.11	4,955	2.848	3.256	5.909	3.419	3.498	6.046
Cargo 1	5/17/18	3,615	87	1/8/19	236	—	—	—	—	—	—	7.74	3,615	2.782	3.263	5.914	—	—	—
Cargo 2	5/17/18	3,635	108	1/8/19	236	—	—	—	—	—	—	7.74	3,635	2.782	3.263	5.914	—	—	—
Piloted	5/18/18	4,019	132	9/10/18	115	651	6/22/20	1476	158	11/27/20	924	15.92	5,333	3.989	6.848	8.439	3.688	4.385	6.599
Piloted[2]	6/13/18	4,019	132	12/10/18	180	569	7/1/20	1,476	180	12/28/20	929	15.92	5,495	3.989	6.848	8.439	3.688	3.025	5.785

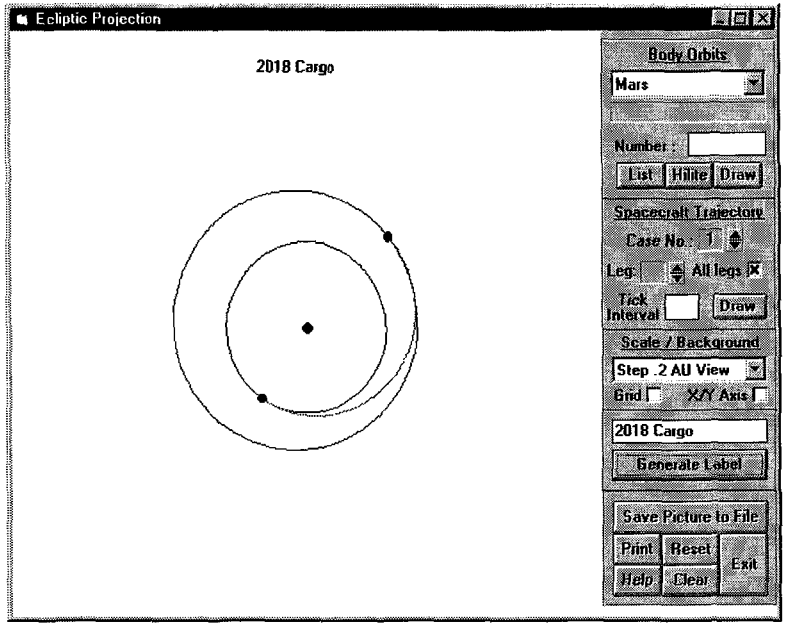
1) Optimal piloted trajectory (minimum initial mass)
2) Latest possible launches designed to 2011/180 day C_3s

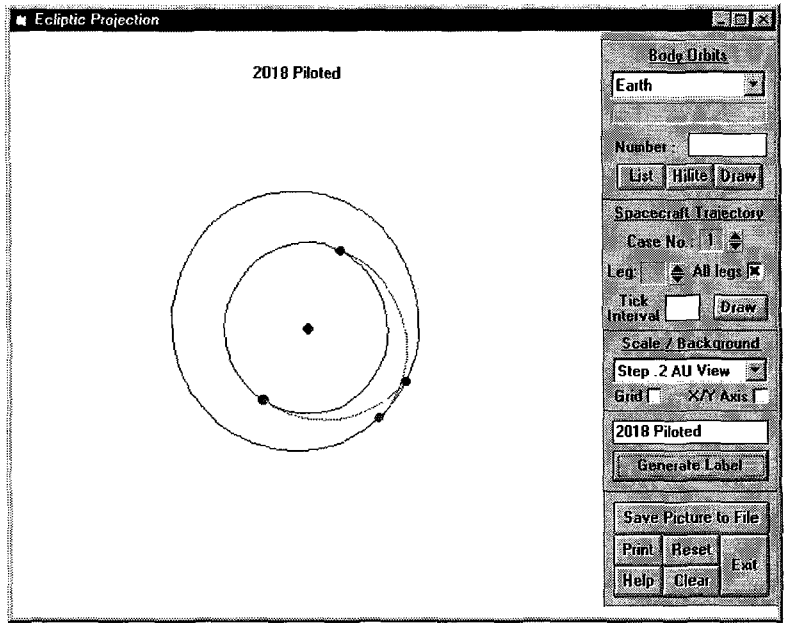
27-day Earth-Mars Departure Window:

Depart:	TOF	Arrival:
5/18/18	115	9/10/18
6/13/18	180	2/10/18

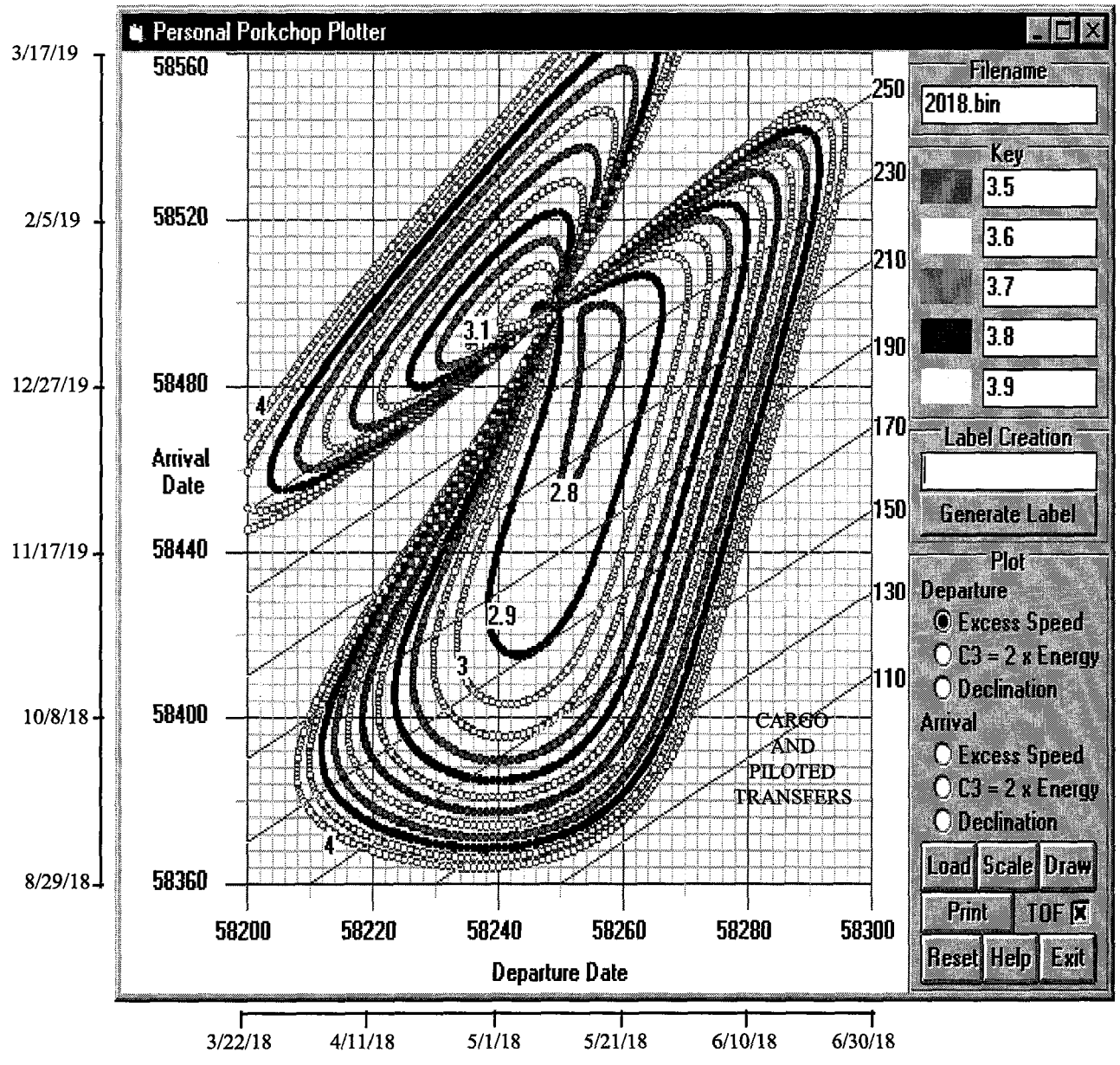
10-day Mars-Earth Return Window:

Depart:	TOF	Arrival:
16/22/20	157	11/27/20
7/1/20	180	12/28/20

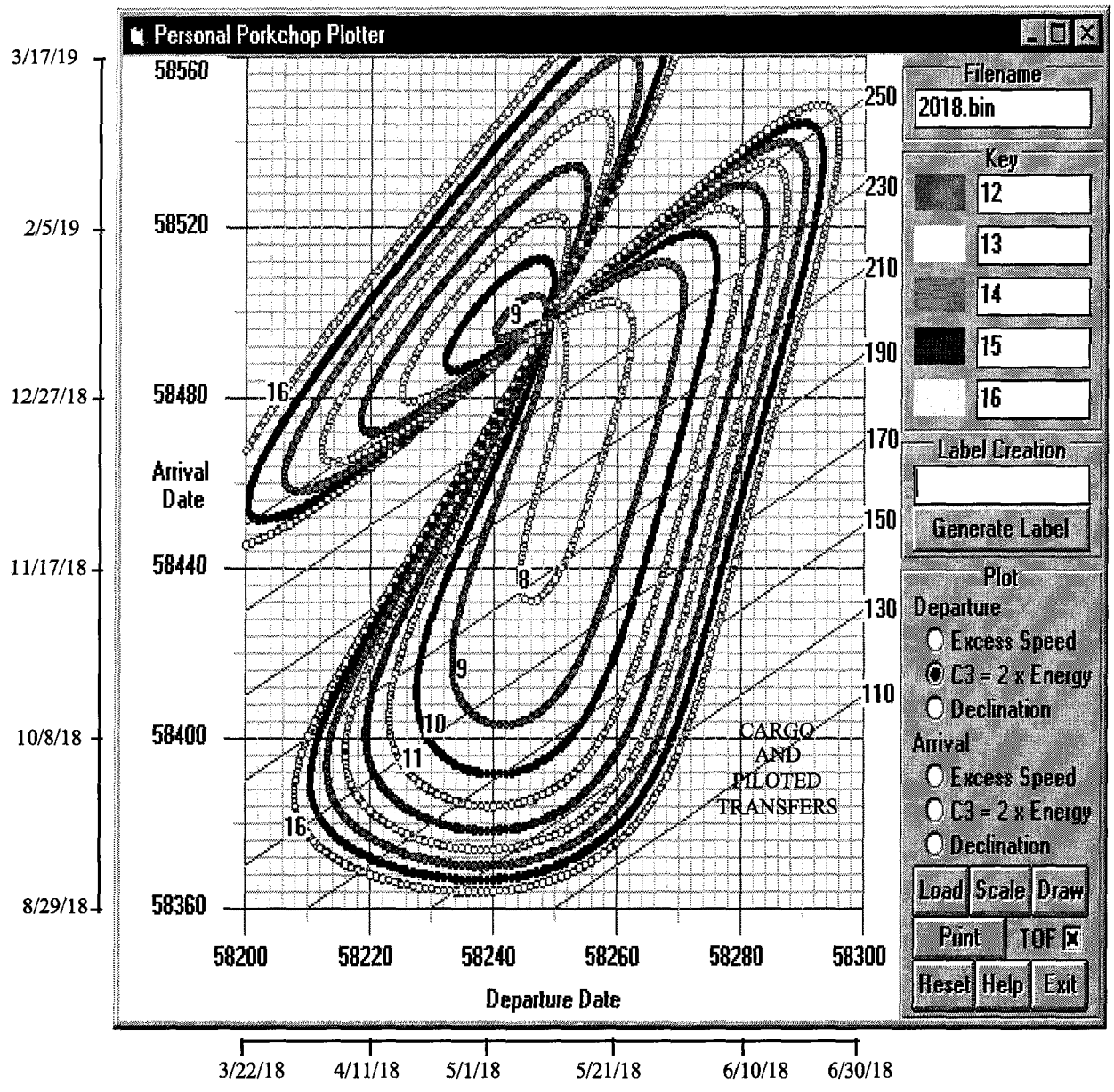




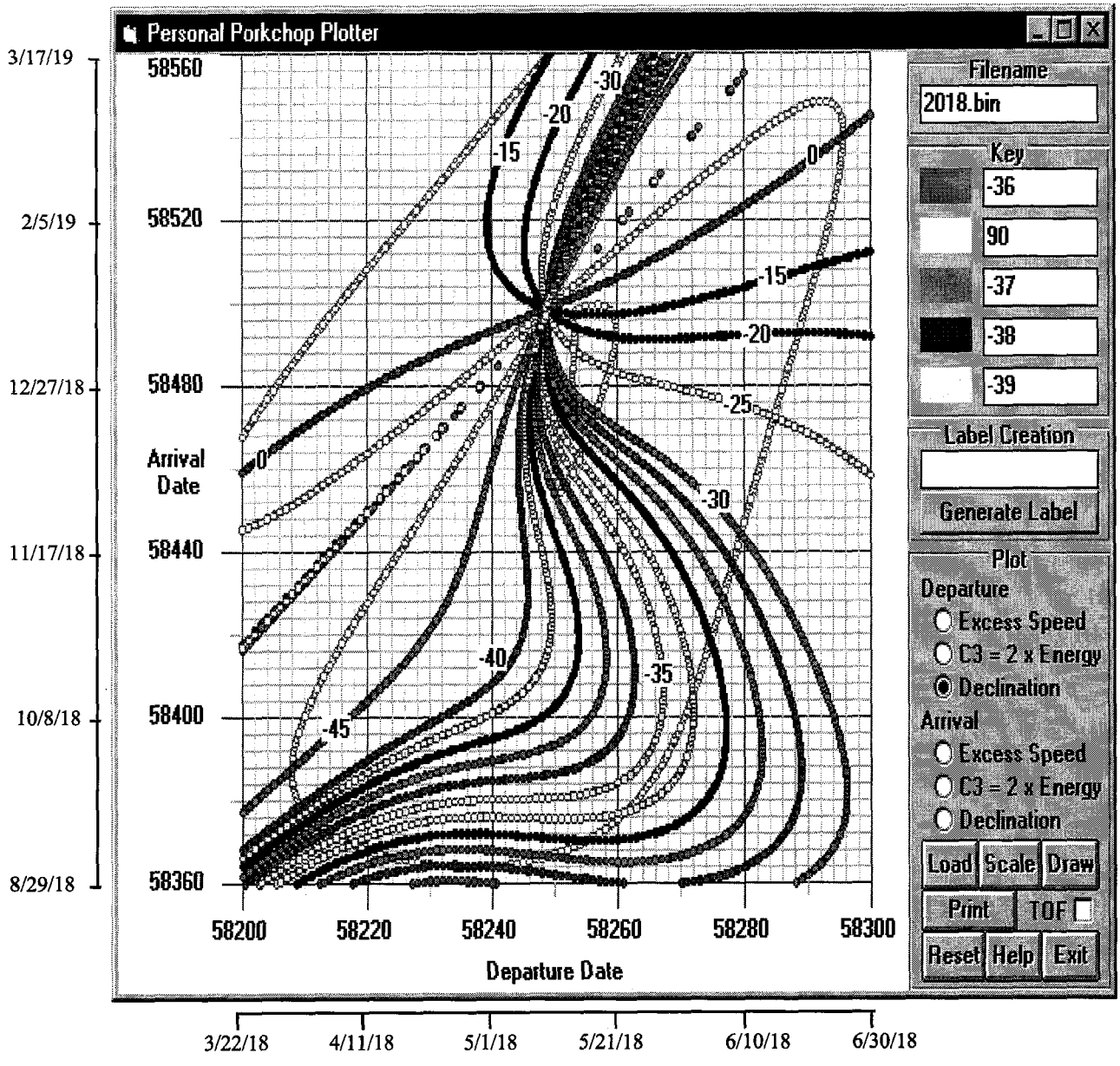
Earth-Mars Trajectories
2018 Conjunction Class
Departure Excess Speed (km/sec)



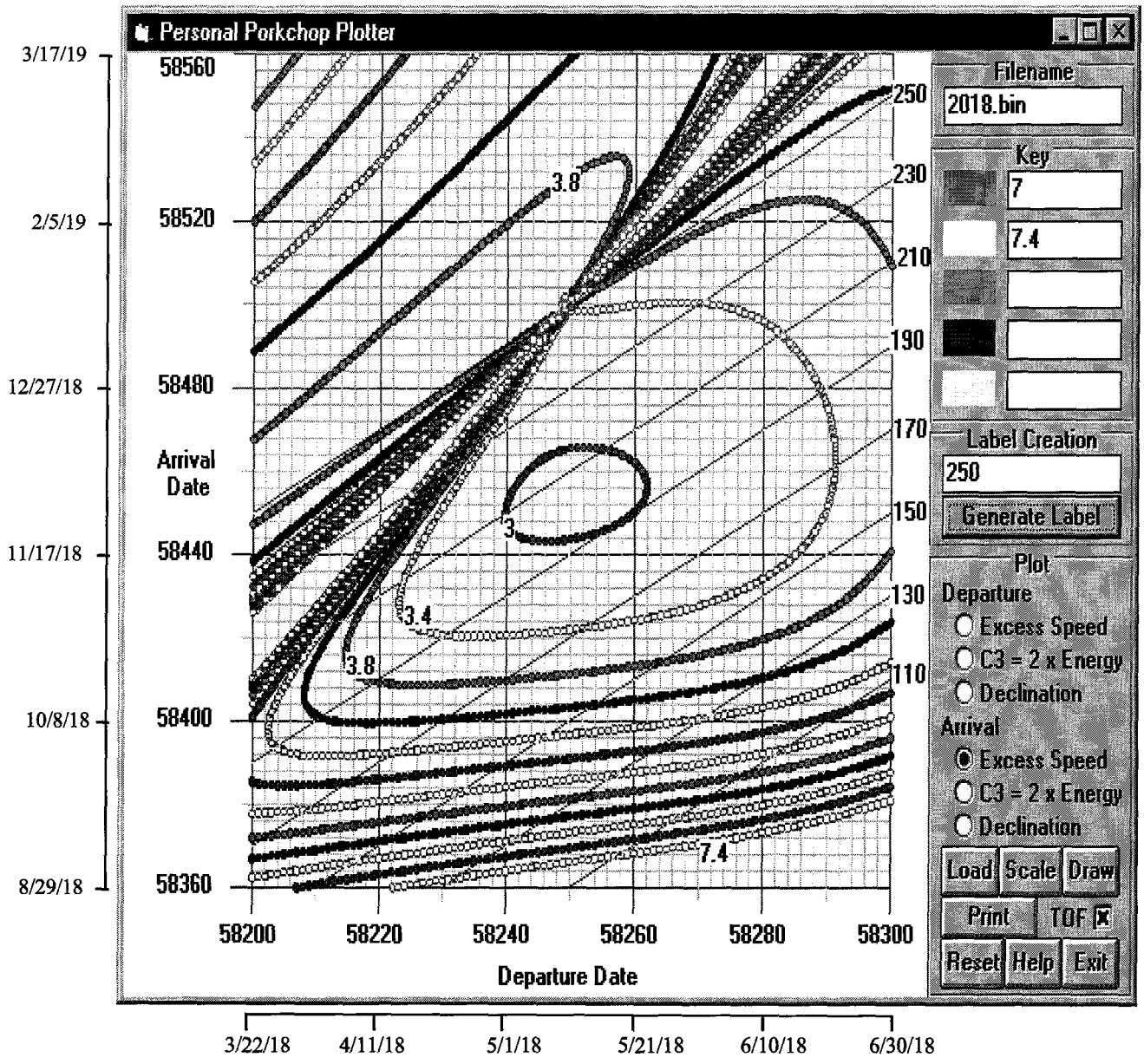
Earth-Mars Trajectories
2018 Conjunction Class
C_3 Departure Energy (km^2/sec^2)



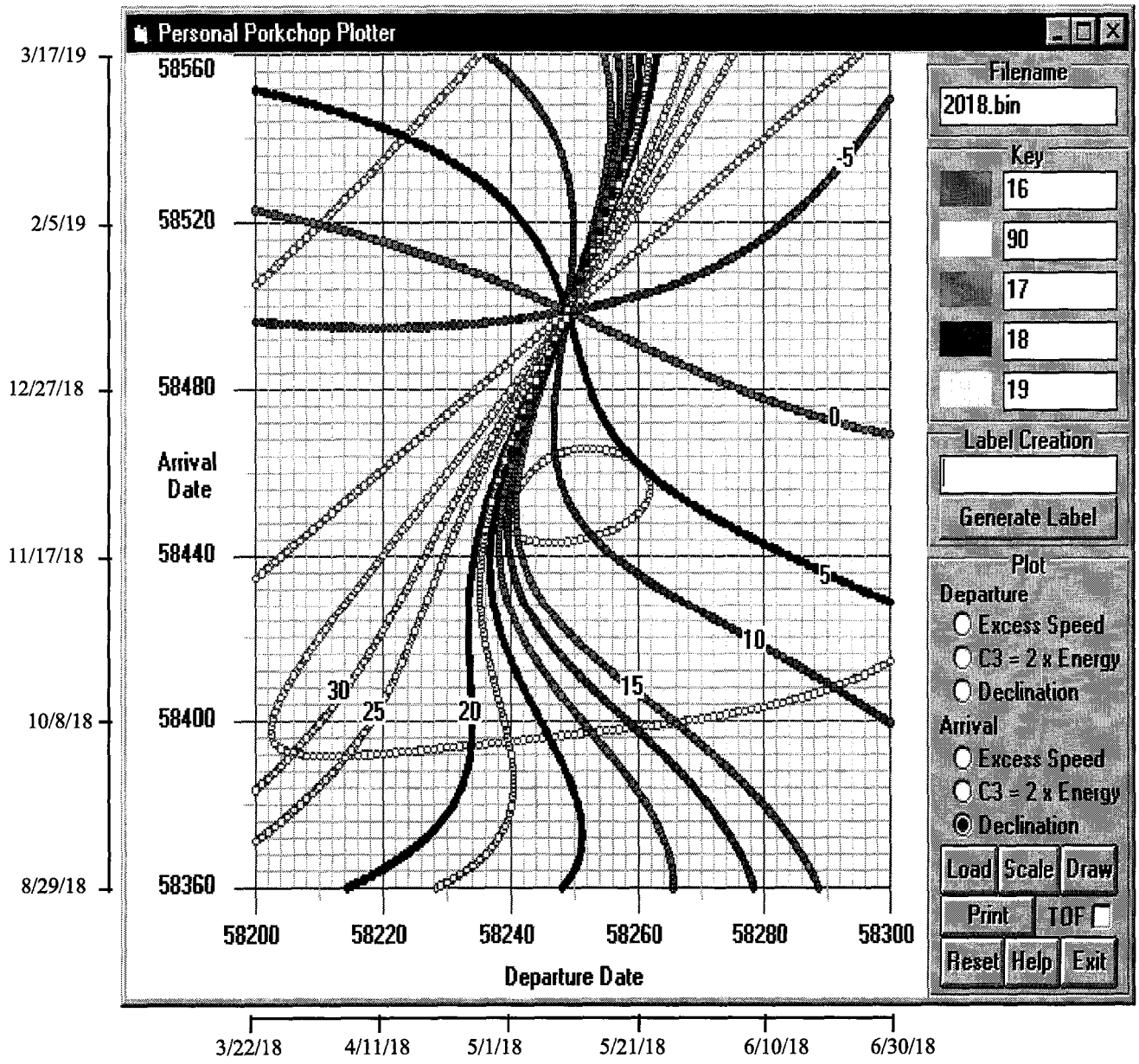
Earth-Mars Trajectories
2018 Conjunction Class
Departure Declination (Degrees)



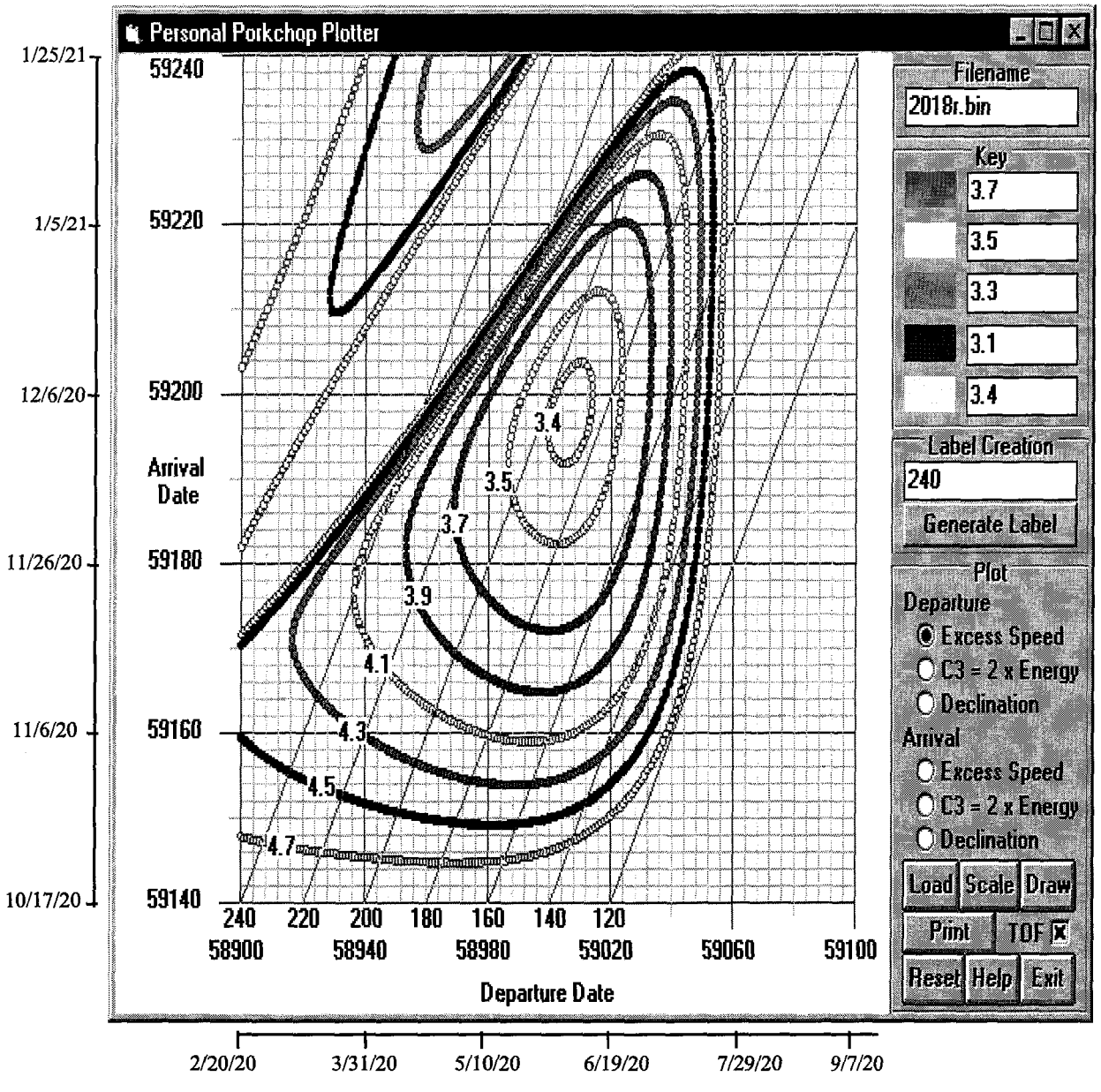
Earth-Mars Trajectories
2018 Conjunction Class
Arrival Excess Speed (km/sec)



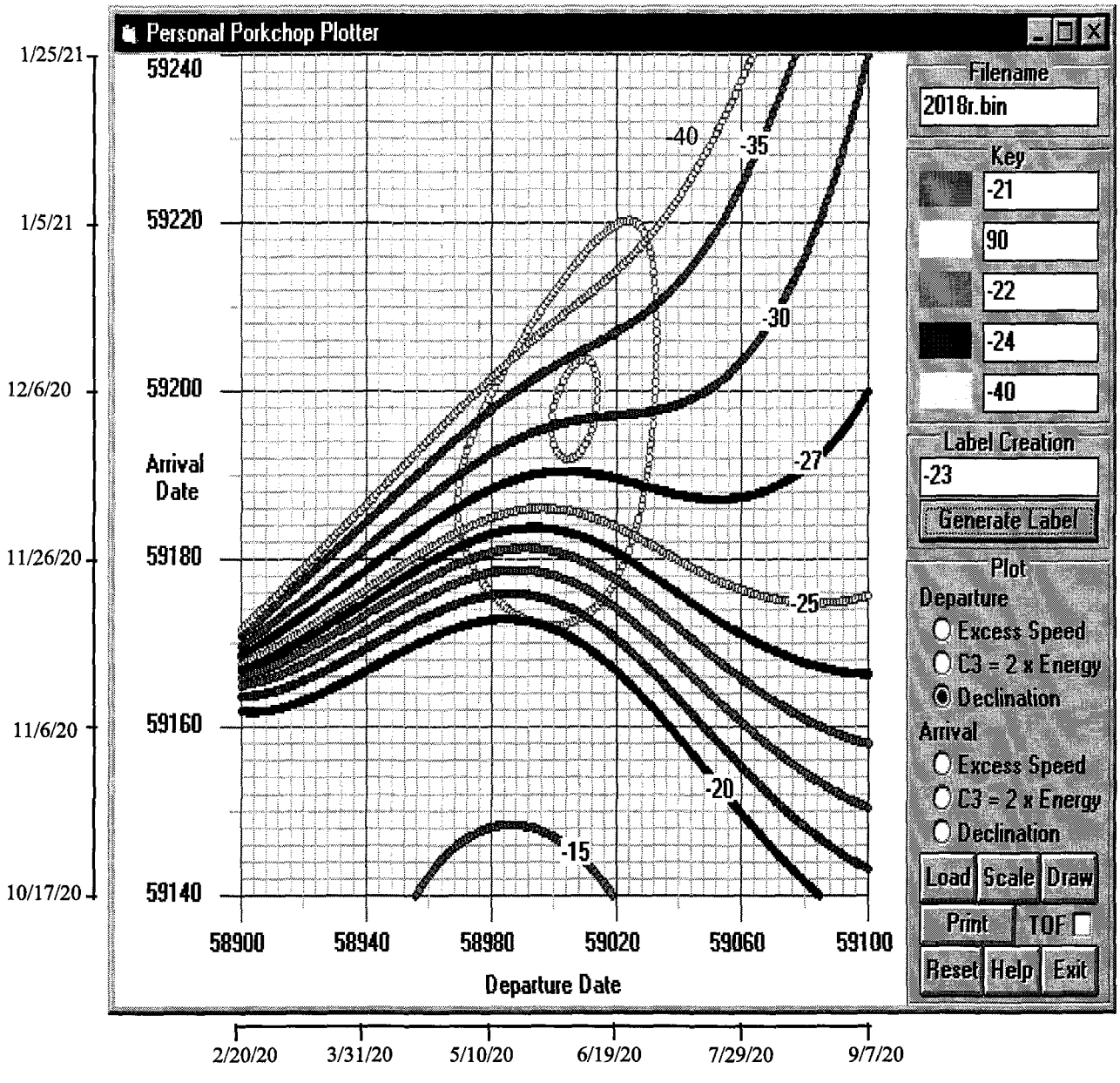
Earth-Mars Trajectories
2018 Conjunction Class
Arrival Declination (Degrees)



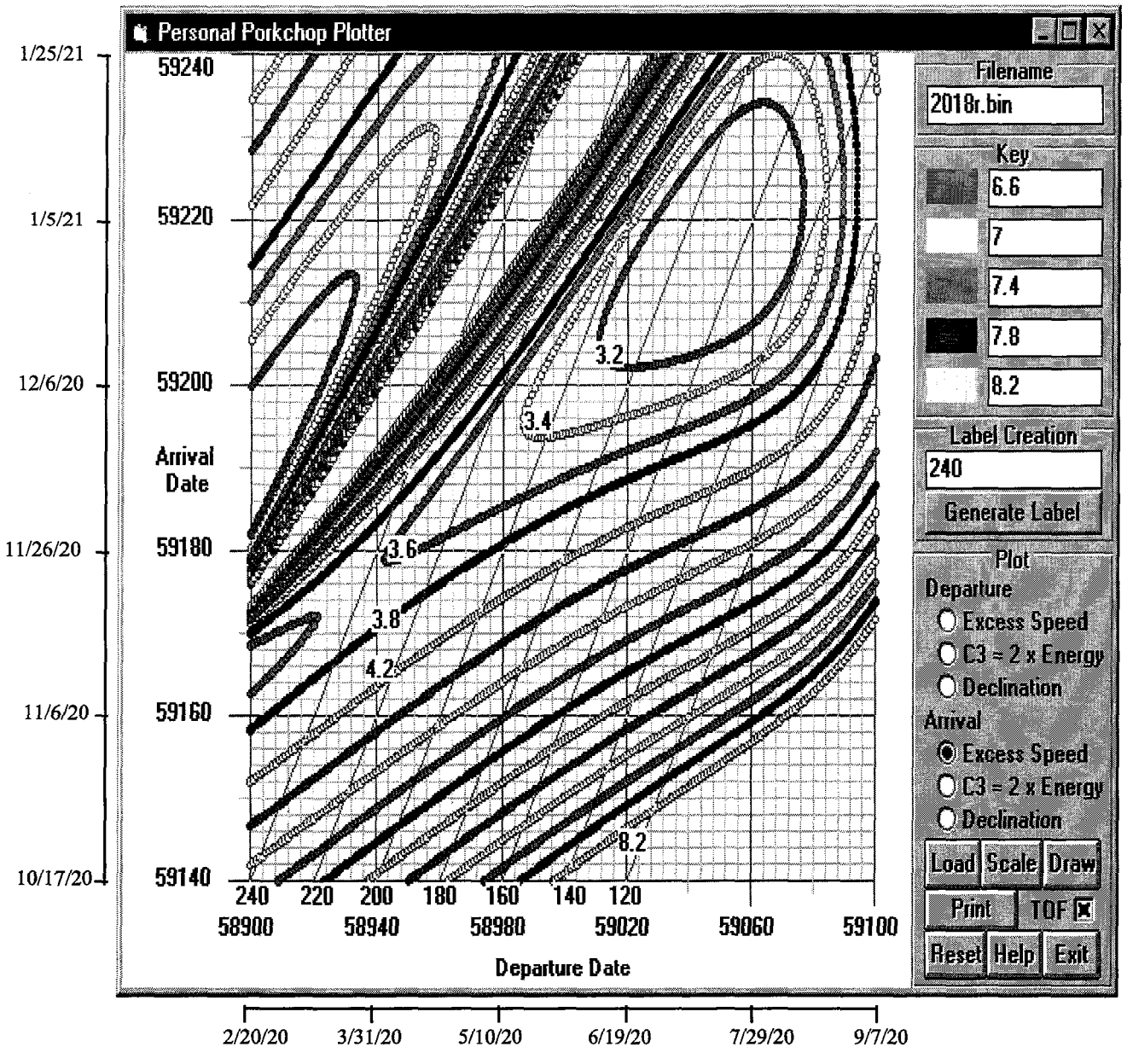
Mars-Earth Trajectories
2020 Conjunction Class
(Returns from 2018 Missions)
Departure Excess Speed (km/sec)



Mars-Earth Trajectories
2020 Conjunction Class
(Returns from 2018 Missions)
Departure Declinations (Degrees)



Mars-Earth Trajectories
2020 Conjunction Class
(Returns from 2018 Missions)
Arrival Excess Speed (km/sec)



Mars-Earth Trajectories
2020 Conjunction Class
(Returns from 2018 Missions)
Arrival Declination (Degrees)

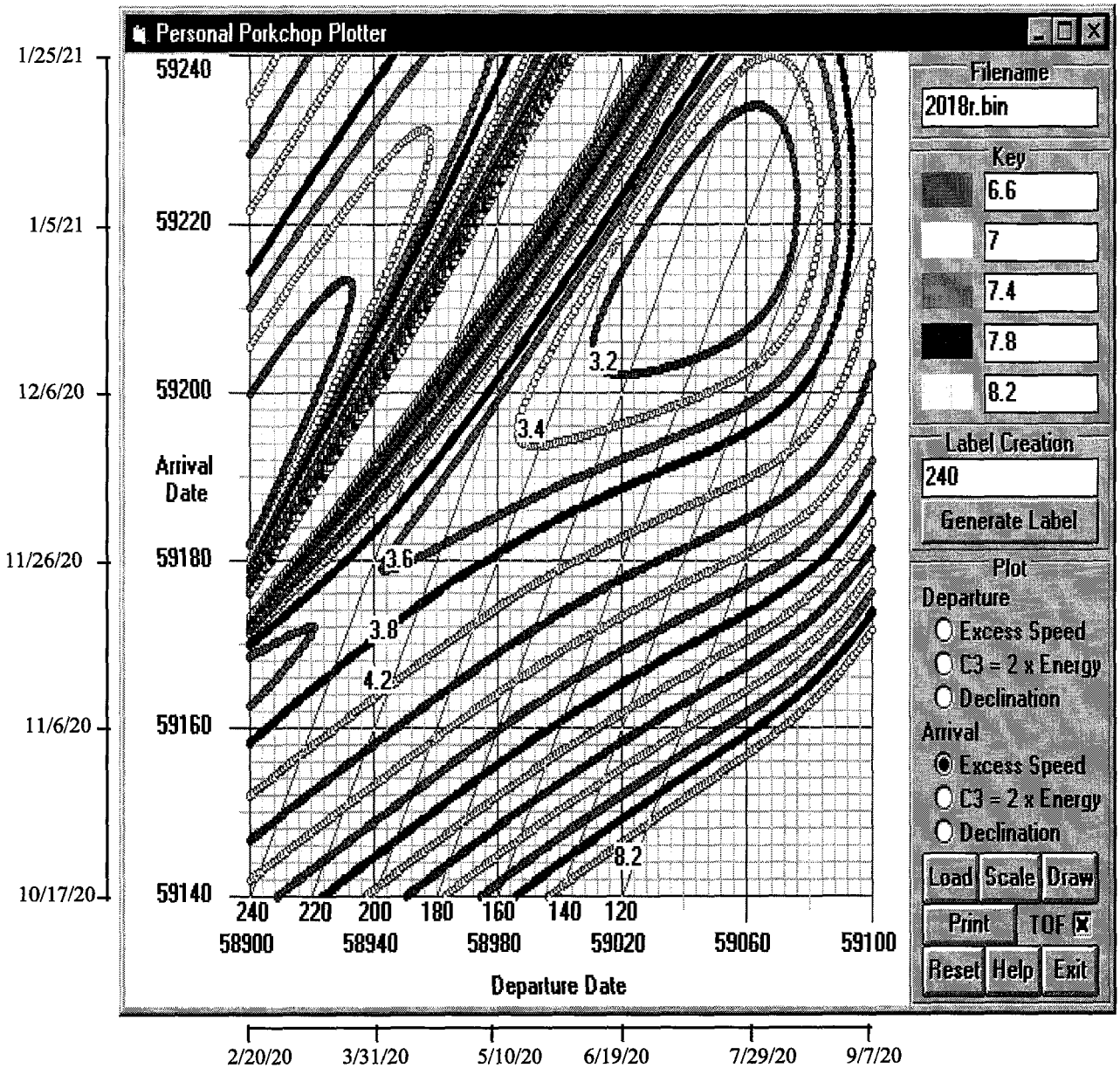


Table 14. 2020 opportunities summary.

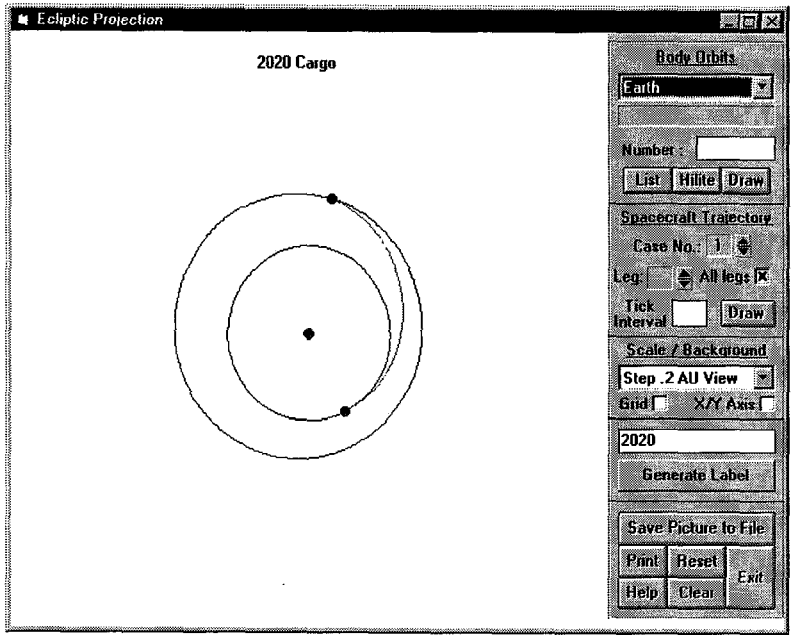
Mission Type	TMI Date (m/d/yr)	TMI ΔV (m/sec)	Vel Losses (m/sec)	Mars Arrival Date (m/d/yr)	Outbd Flight Time (days)	Mars Stay Time (days)	Mars Departure Date (m/d/yr)	TEI ΔV (m/sec)	Return Time (days)	Return Date (m/d/yr)	Total Mission Duration (days)	C_3 (km^2/sec^2)	Total ΔV (m/sec)	Depart. V_∞ @ Earth (km/sec)	Arrival V_∞ @ Mars (km/sec)	Arrival Velocity @ Mars (km/sec)	Depart. V_∞ @ Mars (km/sec)	Arrival V_∞ @ Earth (km/sec)	Arrival Velocity @ Earth (km/sec)
Cargo 1	7/18/20	3,877	109	1/27/21	193	—	—	—	—	—	—	13.17	3,877	3.630	2.857	5.699	—	—	—
Cargo 2	7/18/20	3,903	135	1/27/21	193	—	—	—	—	—	—	13.17	3,903	3.630	2.857	5.699	—	—	—
Piloted[1]	7/19/20	3,899	120	1/15/21	180	562	7/31/22	1,706	180	1/27/23	922	13.43	5,605	3.665	3.154	5.854	4.048	5.282	7.226
Piloted	7/24/20	4,019	132	12/22/20	151	586	7/31/22	1,706	180	1/27/23	917	15.92	5,725	3.989	4.270	6.523	4.048	5.282	7.226
Piloted[2]	8/4/20	4,019	132	1/31/21	180	546	7/31/22	1,706	180	1/27/23	906	15.92	5,725	3.989	4.270	6.523	4.048	5.282	7.226

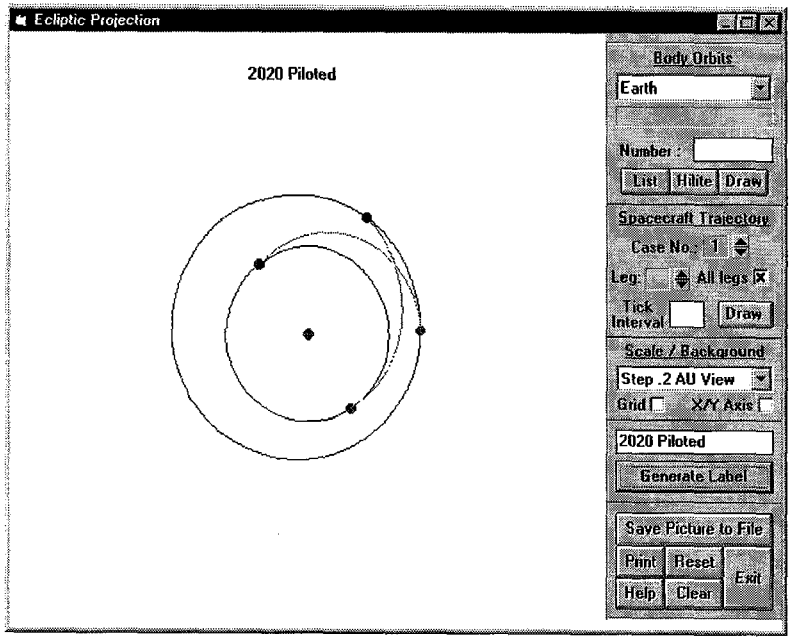
1) Optimal piloted trajectory (minimum initial mass)
2) Latest possible launches designed to 2011/180 day C_3s

12-day Earth-Mars Departure Window:

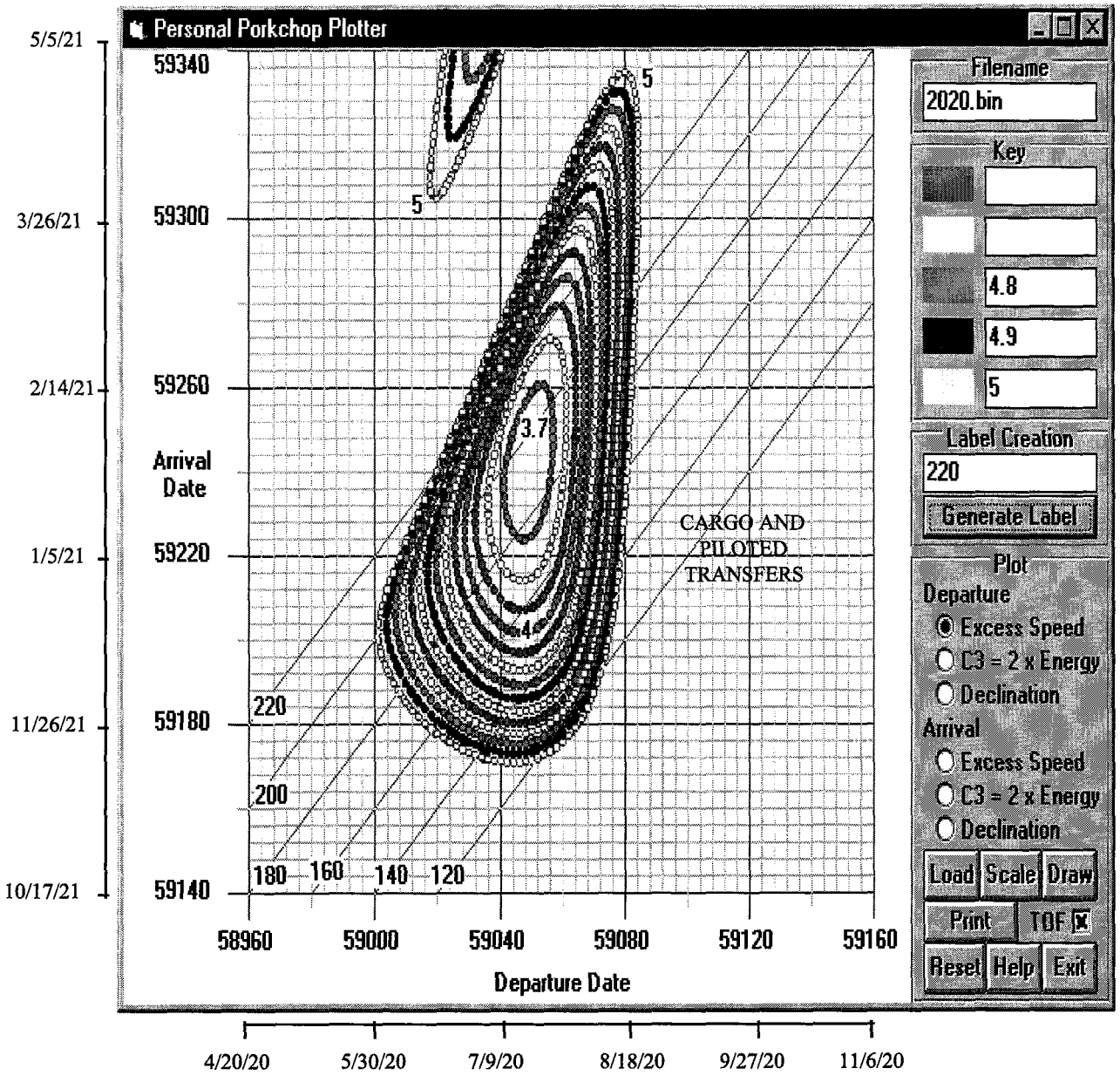
Depart:	TOF	Arrive:
7/24/20	151	12/22/20
8/4/20	180	1/31/21

1-day Mars-Earth Return Window
at minimum departure velocity
and 180 day TOF

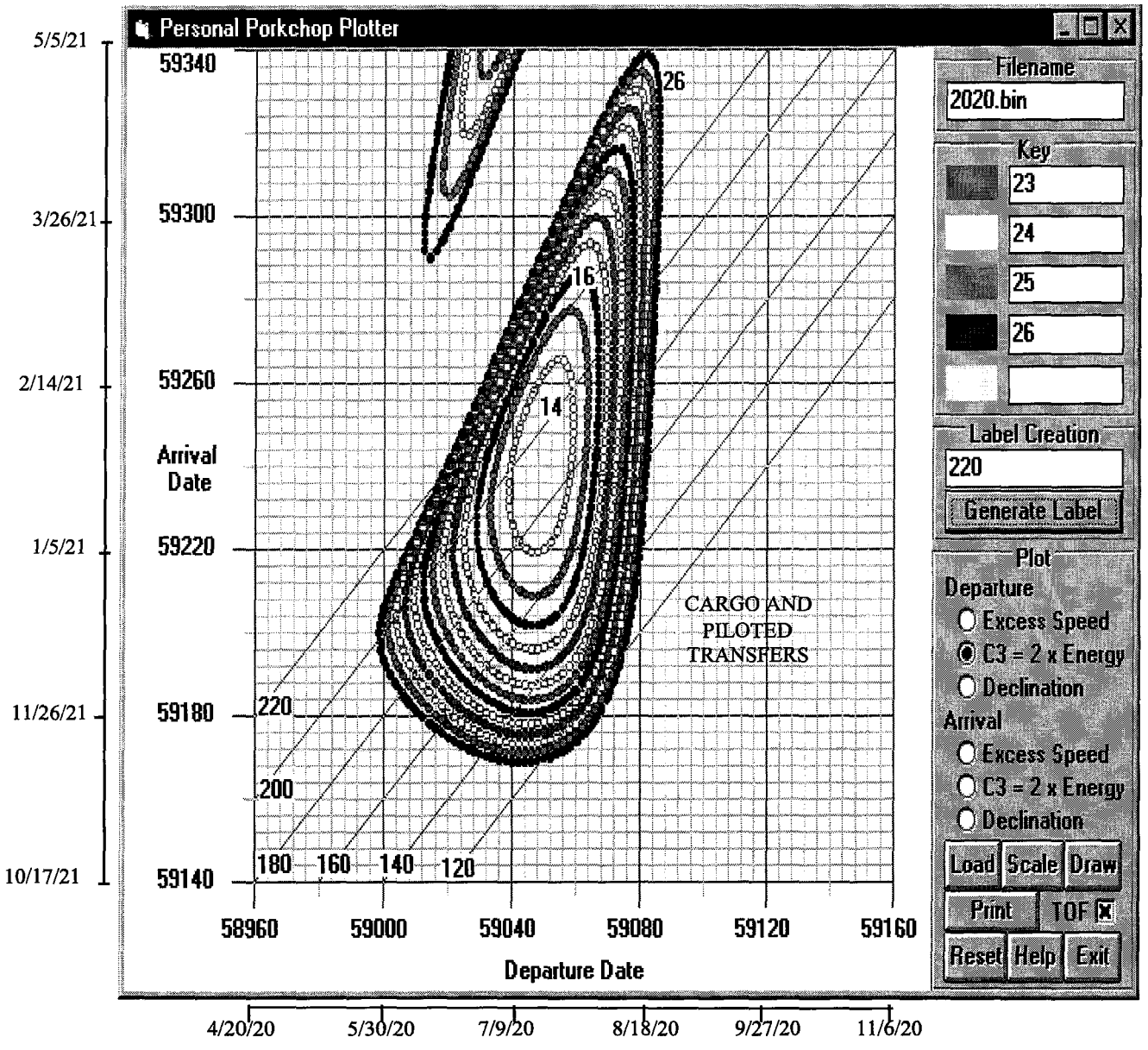




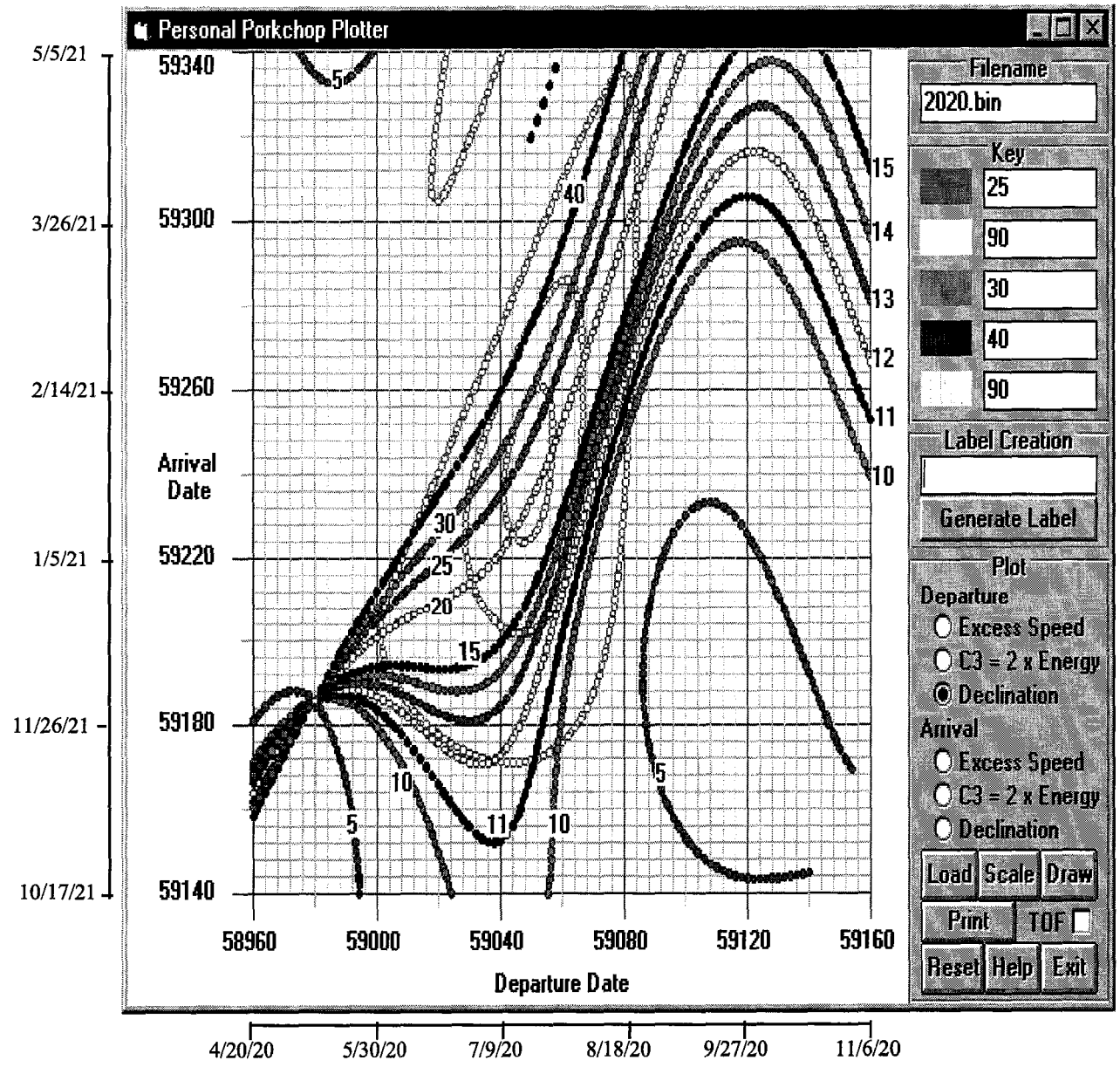
Earth-Mars Trajectories
2020 Conjunction Class
Departure Excess Speed (km/sec)



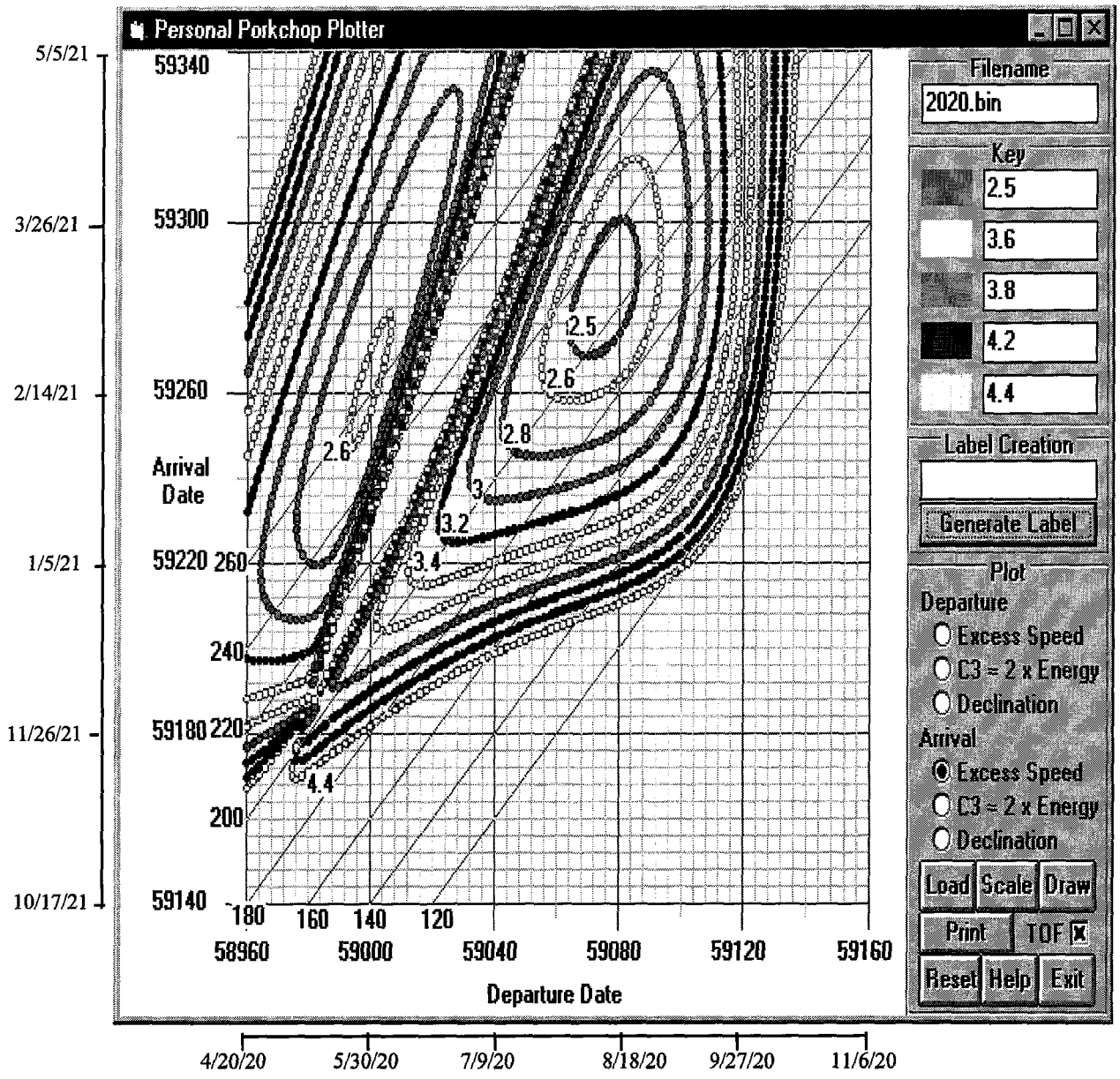
Earth-Mars Trajectories
2020 Conjunction Class
C_3 Departure Energy (km^2/sec^2)



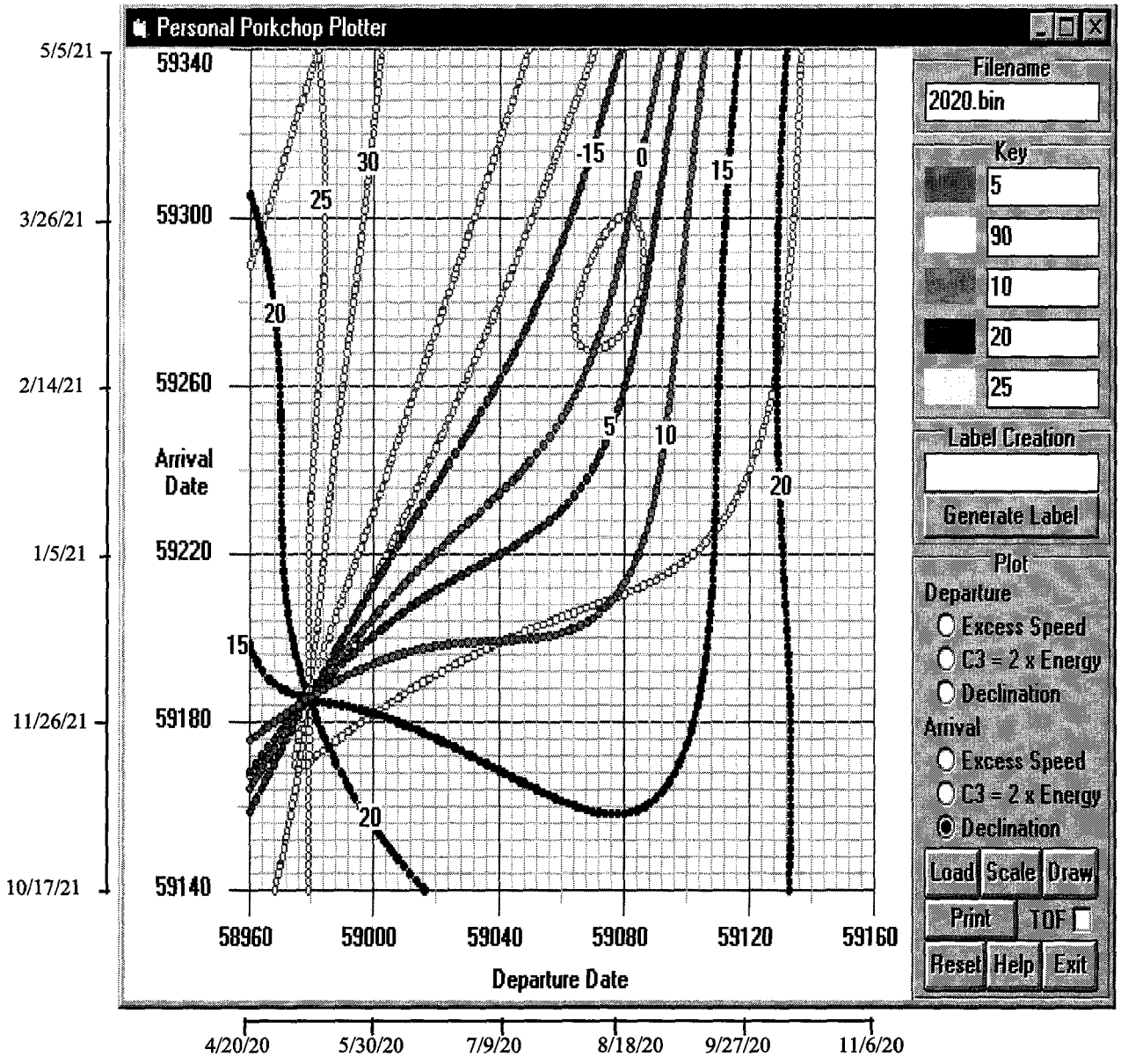
Earth-Mars Trajectories
2020 Conjunction Class
Departure Declination (Degrees)



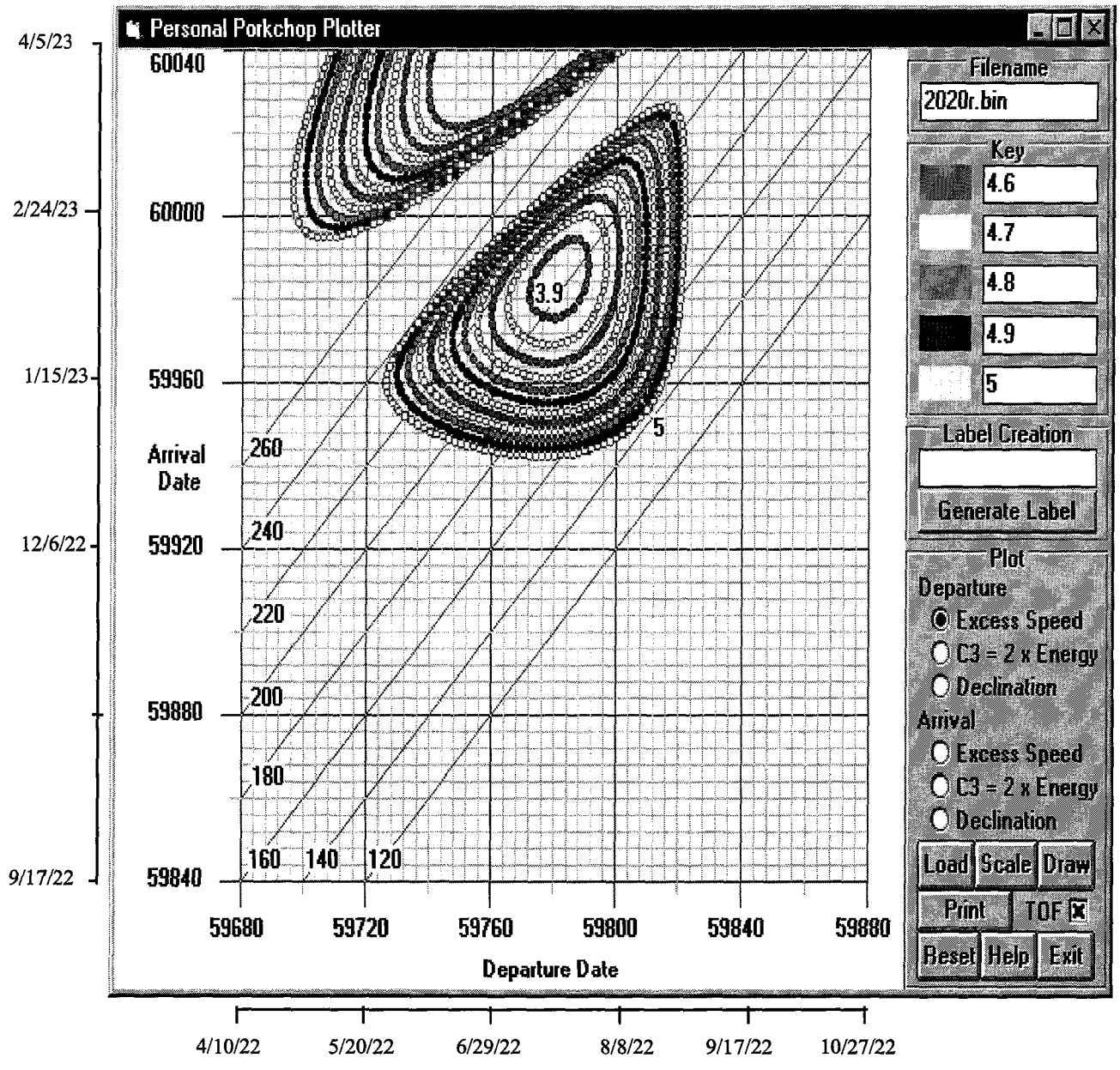
Earth-Mars Trajectories
2020 Conjunction Class
Arrival Excess Speed (km/sec)



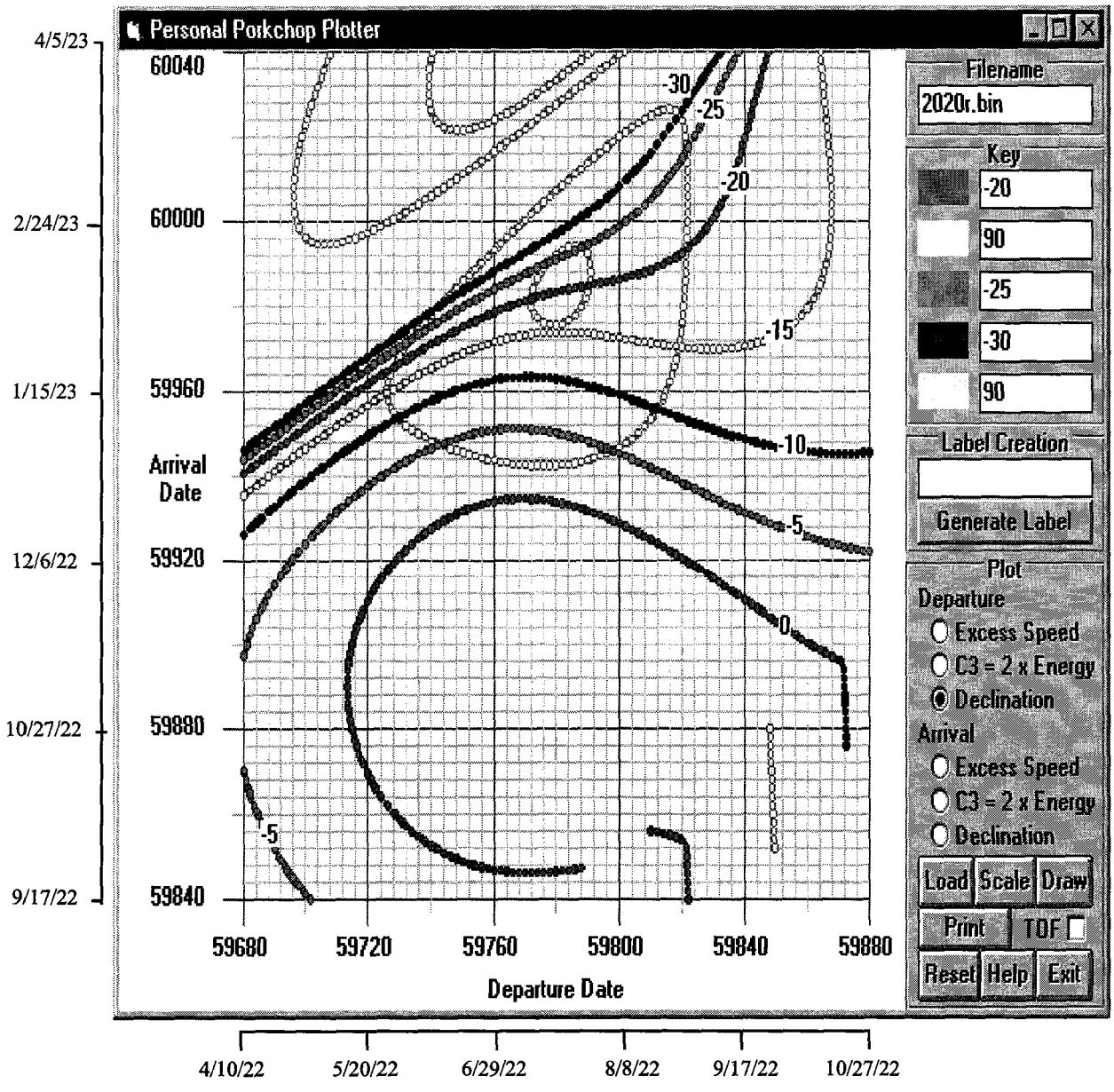
Earth-Mars Trajectories
2020 Conjunction Class
Arrival Declination (Degrees)



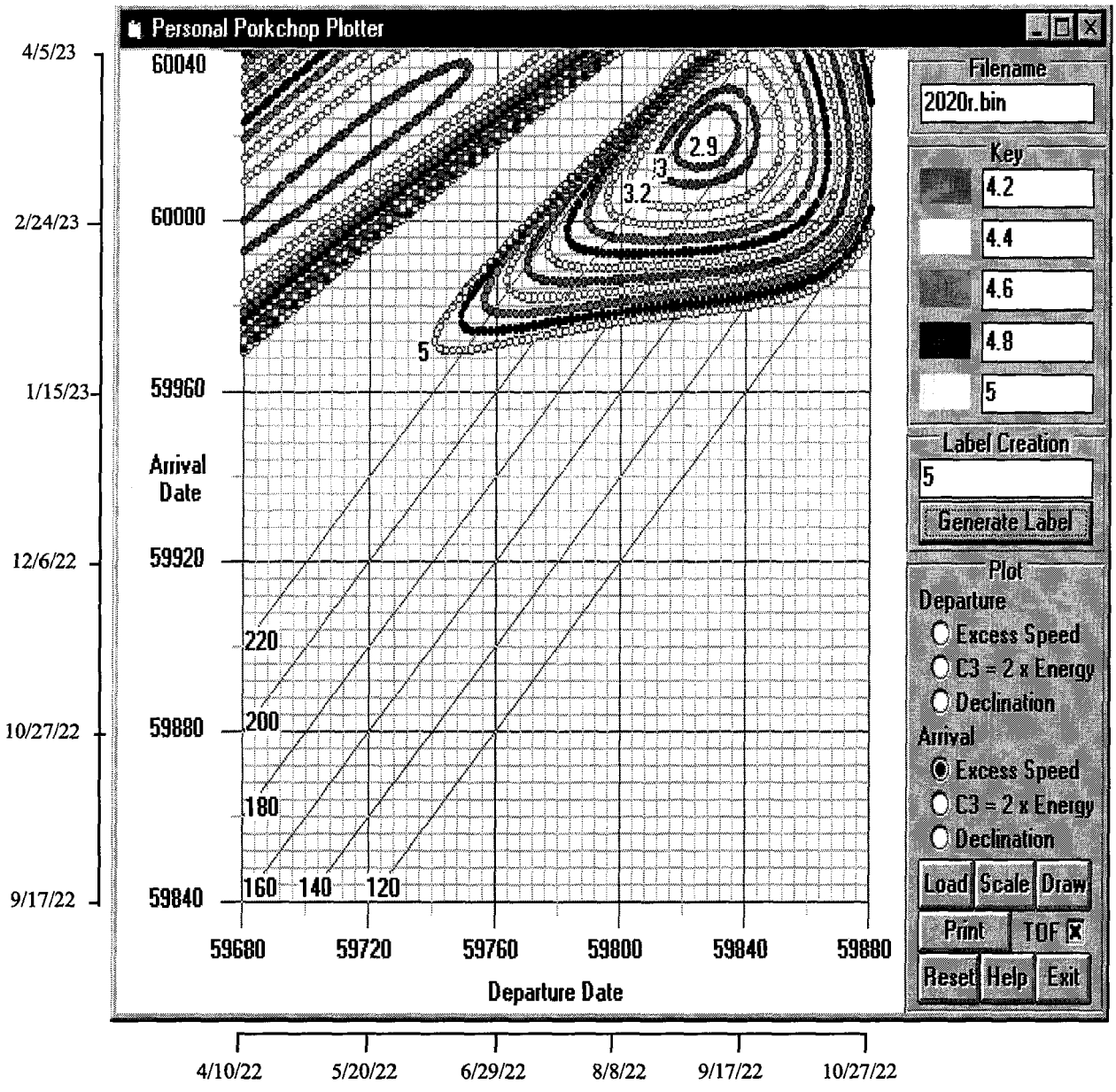
Mars-Earth Trajectories
2022 Conjunction Class
(Returns from 2020 Missions)
Departure Excess Speed (km/sec)



Mars-Earth Trajectories
2022 Conjunction Class
(Returns from 2020 Missions)
Departure Declination (Degrees)



Mars-Earth Trajectories
2022 Conjunction Class
(Returns from 2020 Missions)
Departure Excess Speed (km/sec)



Mars-Earth Trajectories
2022 Conjunction Class
(Returns from 2020 Missions)
Arrival Declination (Degrees)

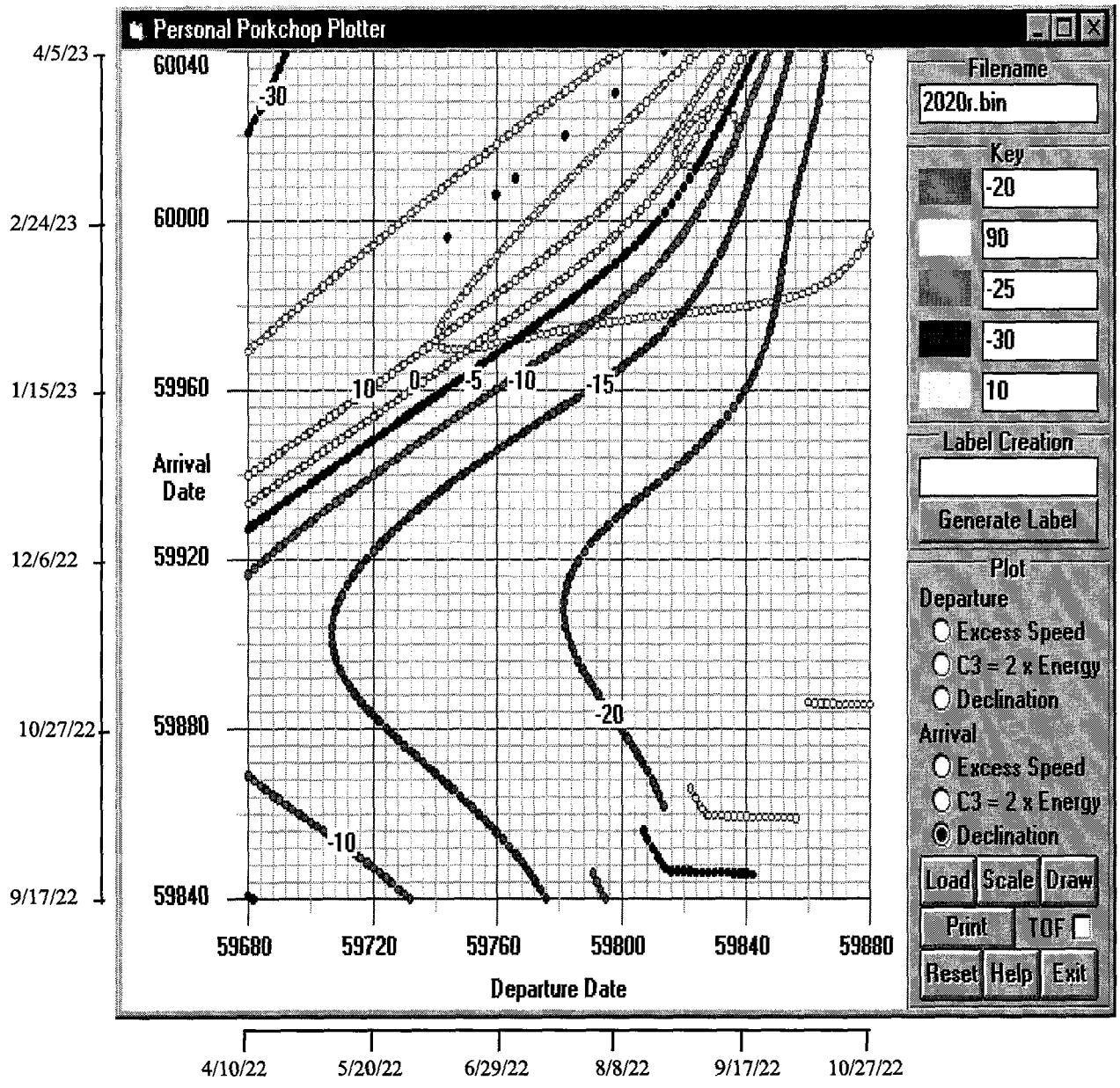
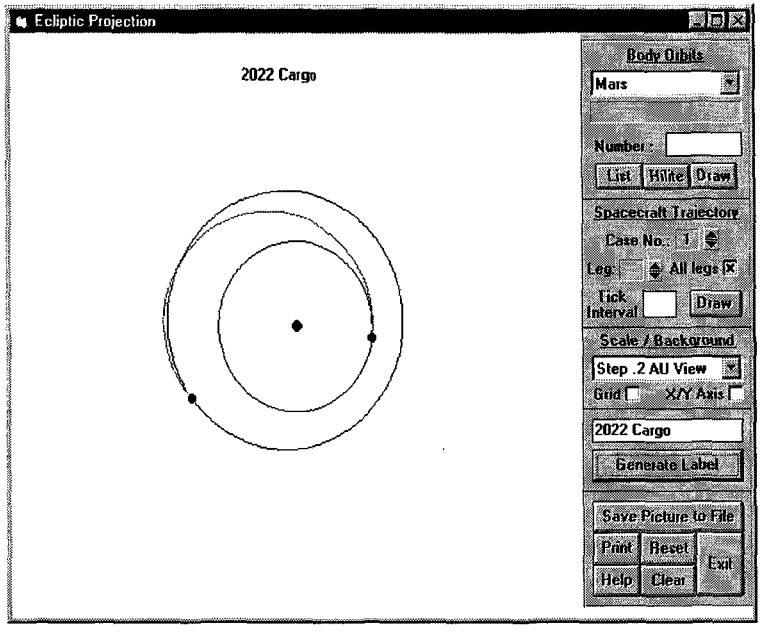
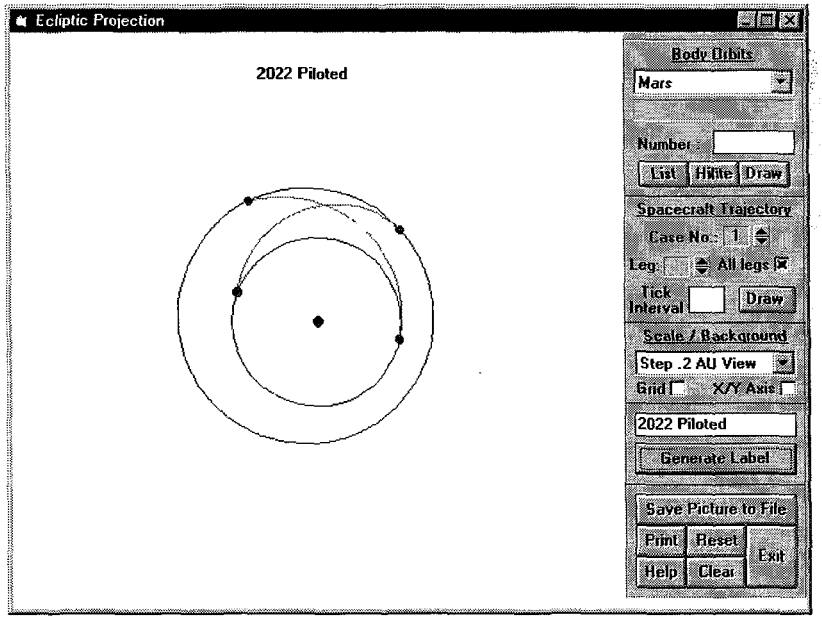


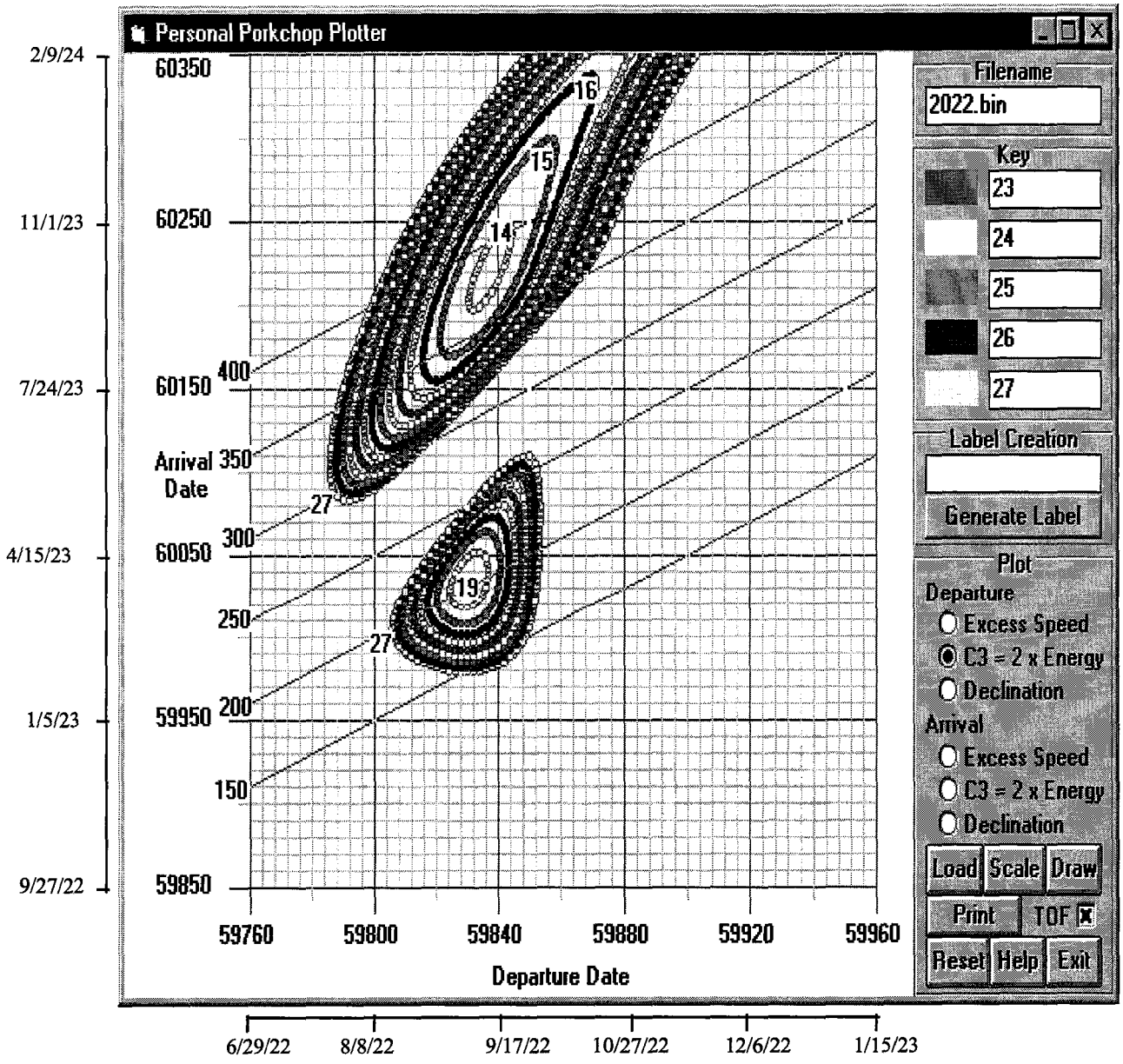
Table 15. 2022 opportunities summary.

Mission Type	TMI Date (m/d/yr)	TMI ΔV (m/sec)	Velocity Losses (m/sec)	Mars Arrival Date (m/d/yr)	Outbound Flight Time (days)	Mars Stay Time (days)	Mars Departure Date (m/d/yr)	TEI ΔV (m/sec)	Return Time (days)	Return Date (m/d/yr)	Total Mission Duration (days)	C_3 (km^2/sec^2)	Total ΔV (m/sec)	Depart. V_∞@ Earth (km/sec)	Arrival V_∞@ Mars (km/sec)	Arrival Velocity @ Mars (km/sec)	Depart. V_∞@ Mars (km/sec)	Arrival V_∞@ Earth (km/sec)	Arrival Velocity @ Earth (km/sec)
Cargo 1	9/14/22	3,906	112	10/2/23	383	—	—	—	—	—	—	13.79	3,906	3.7137	3.074	5.811	—	—	—
Cargo 2	9/14/22	3,933	138	10/2/23	383	—	—	—	—	—	—	13.79	3,933	3.7137	3.074	5.811	—	—	—
Piloted	9/10/22	4,198	152	3/9/23	180	543	9/2/24	1,860	180	3/1/25	903	19.63	6,058	4.4306	4.621	6.758	4.279	7.618	9.075

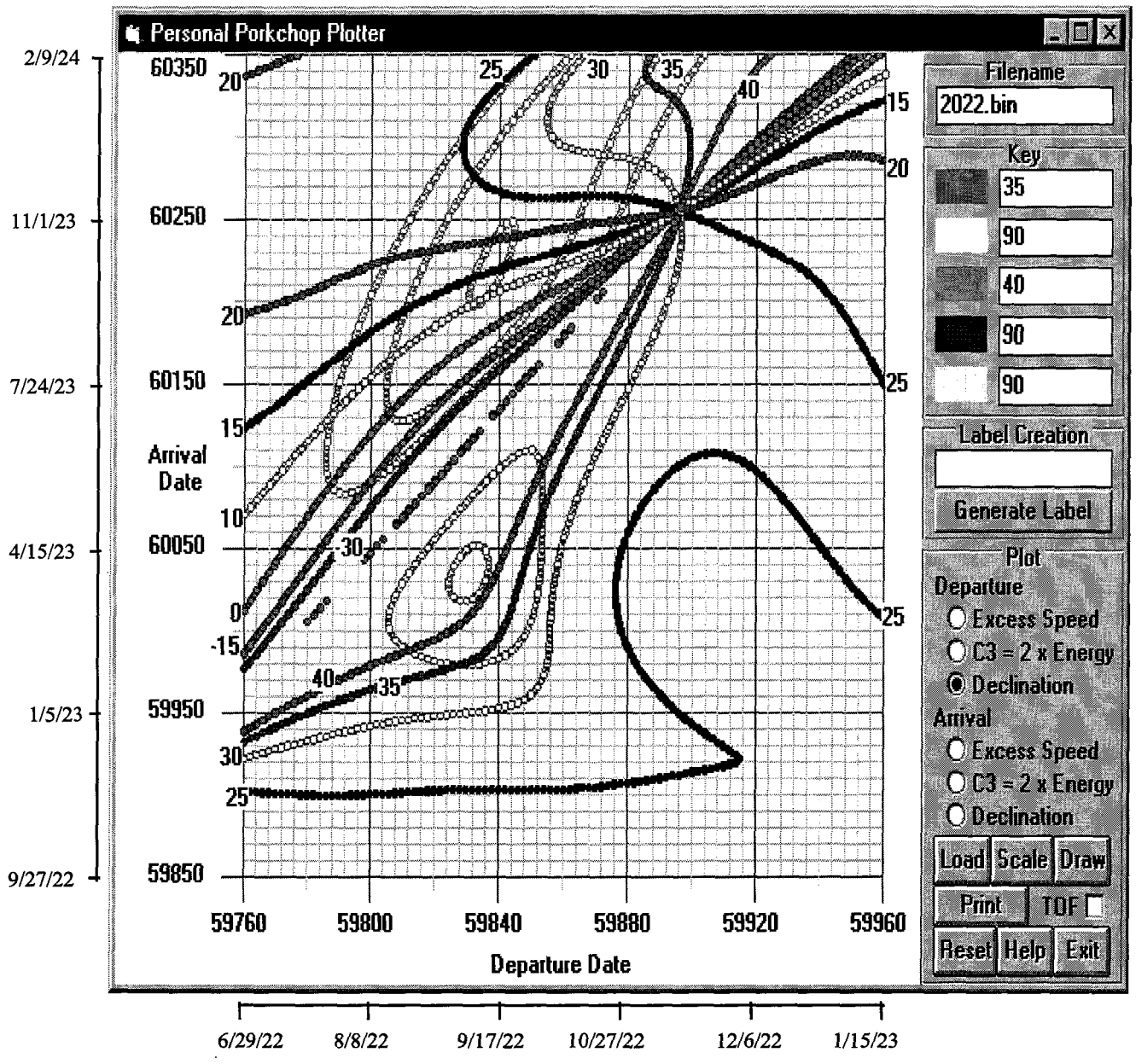




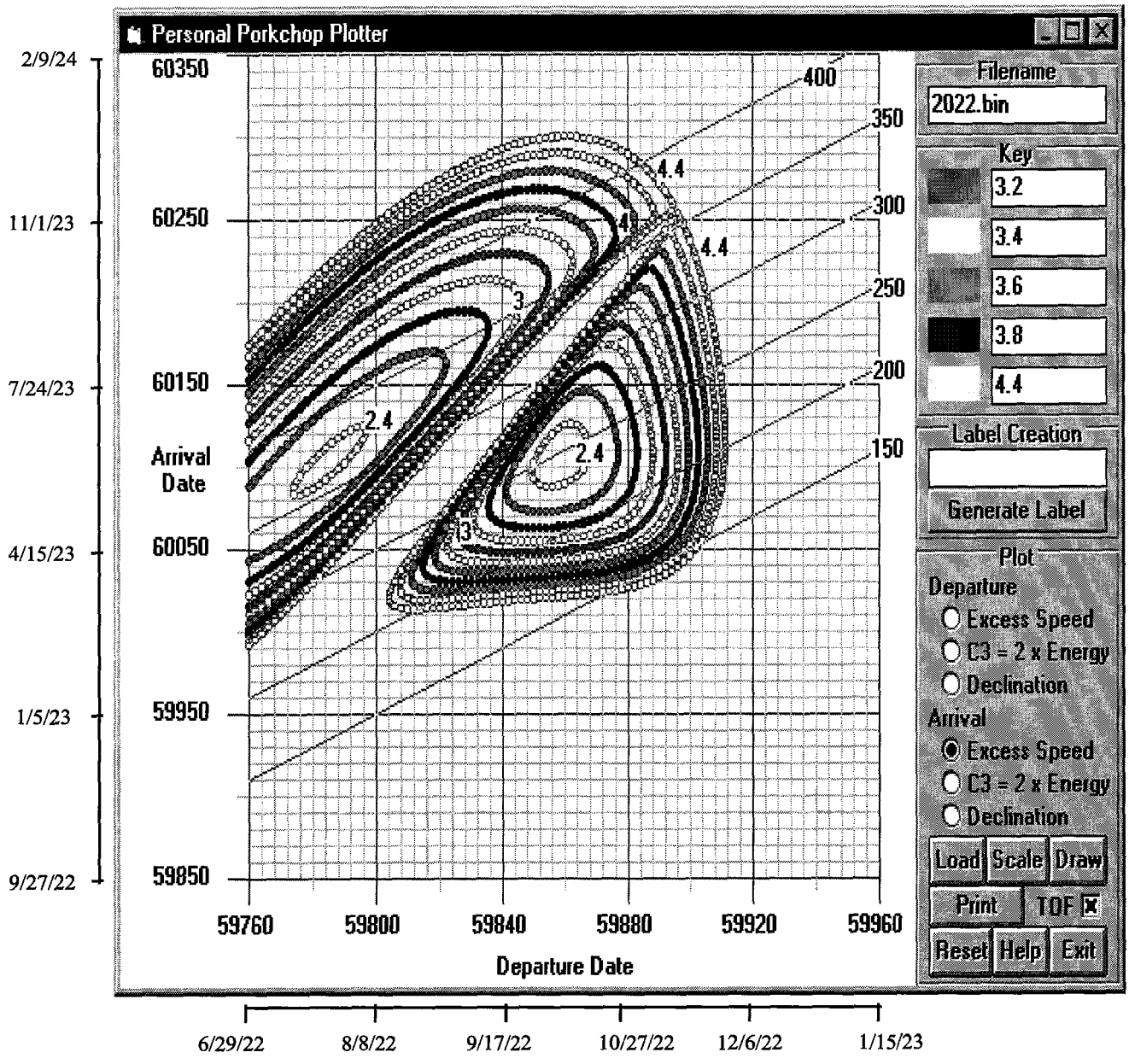
Earth-Mars Trajectories
2022 Conjunction Class
C_3 Departure Energy (km^2/sec^2)



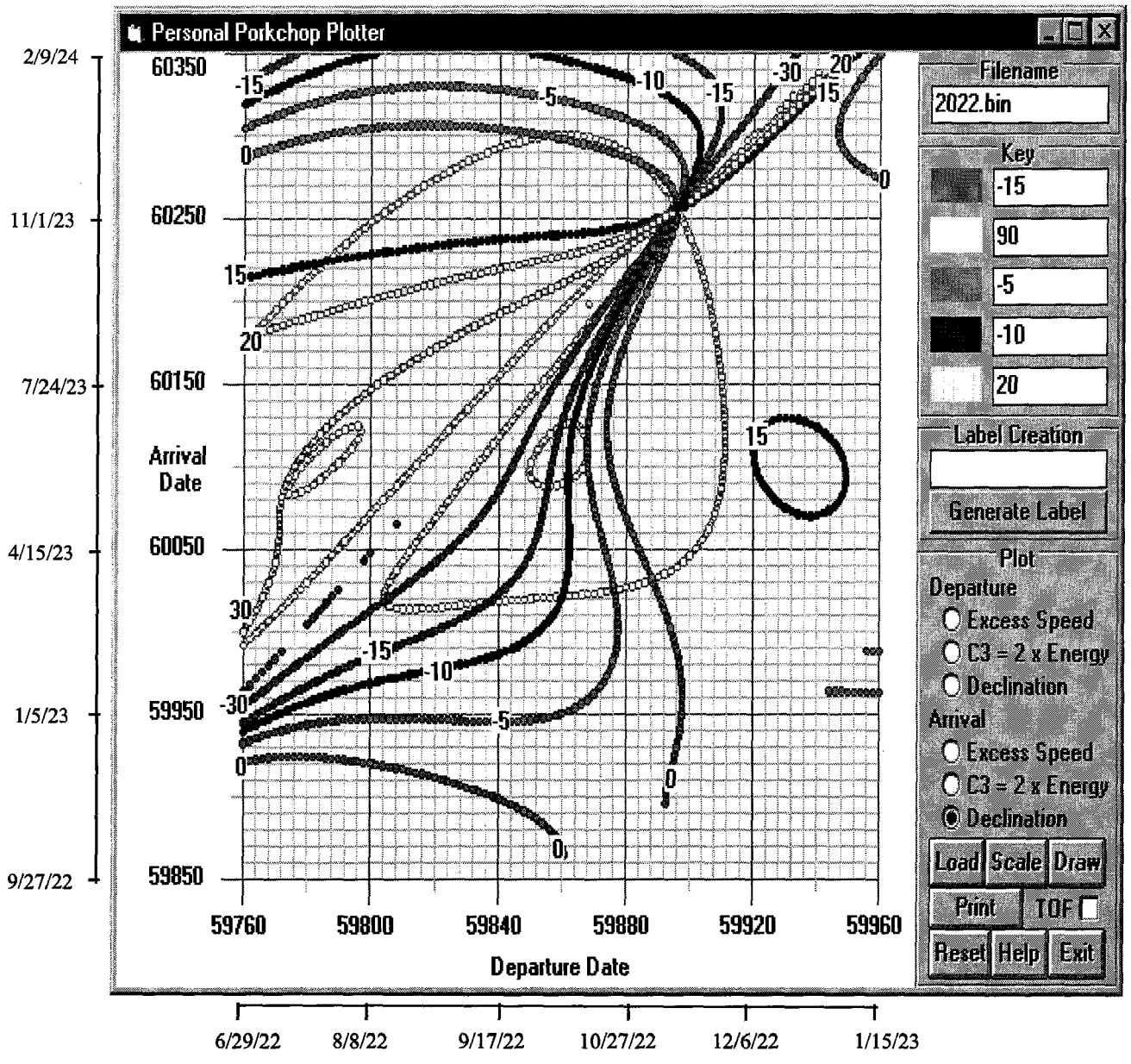
Earth-Mars Trajectories
2022 Conjunction Class
Departure Declinations (Degrees)



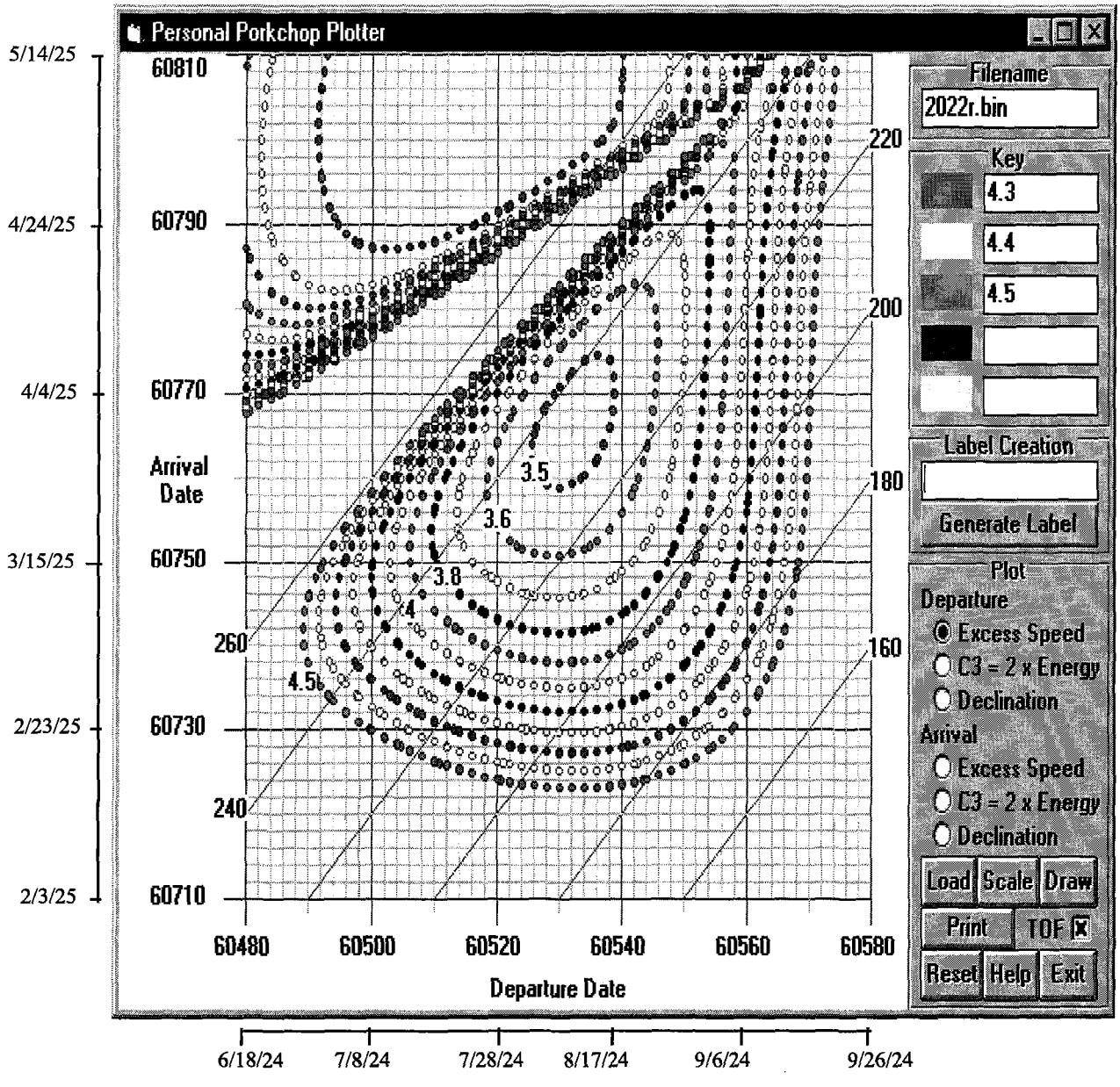
Earth-Mars Trajectories
2022 Conjunction Class
Arrival Excess Speed (km/sec)



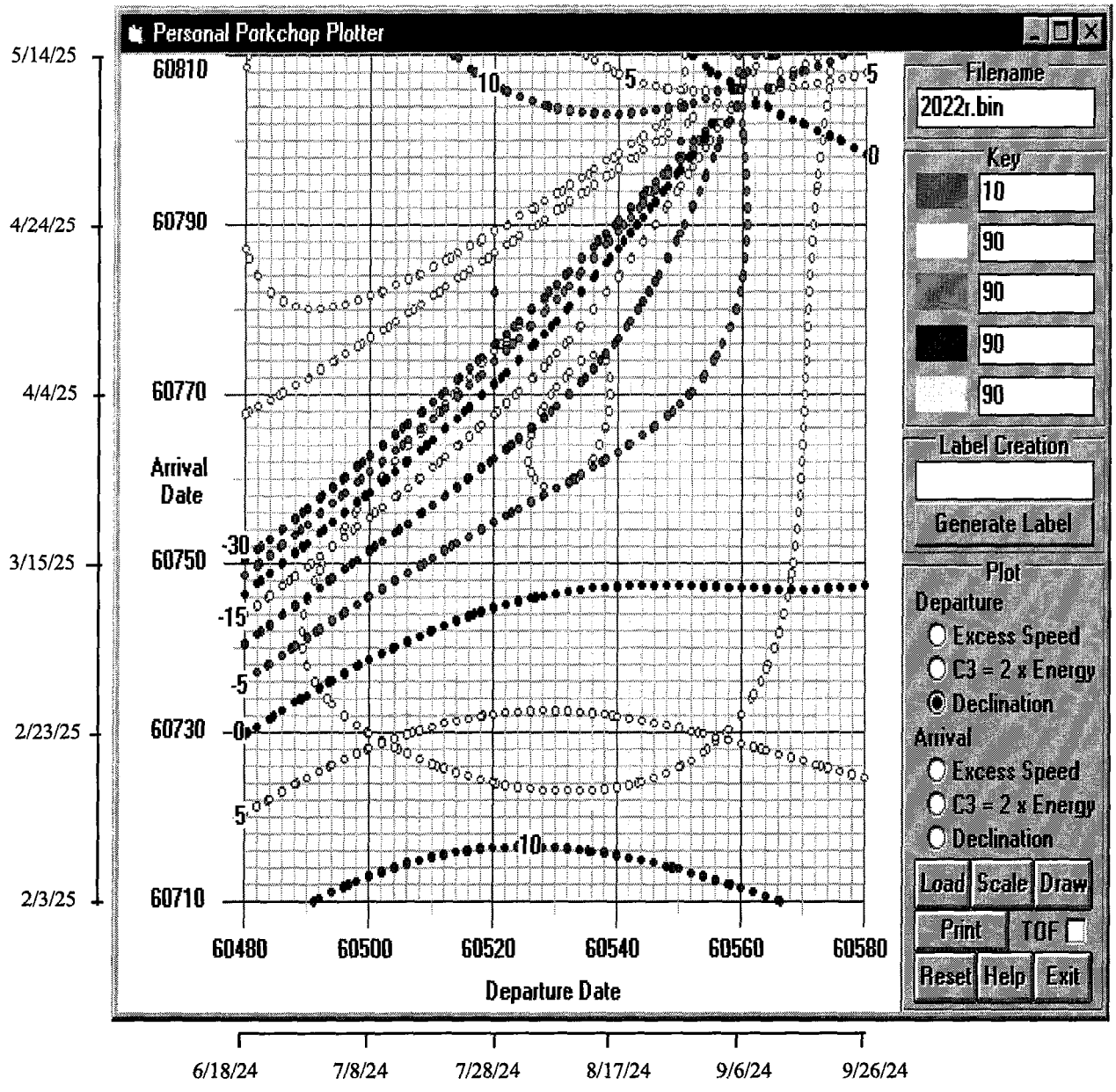
Earth-Mars Trajectories
2022 Conjunction Class
Arrival Declination (Degrees)



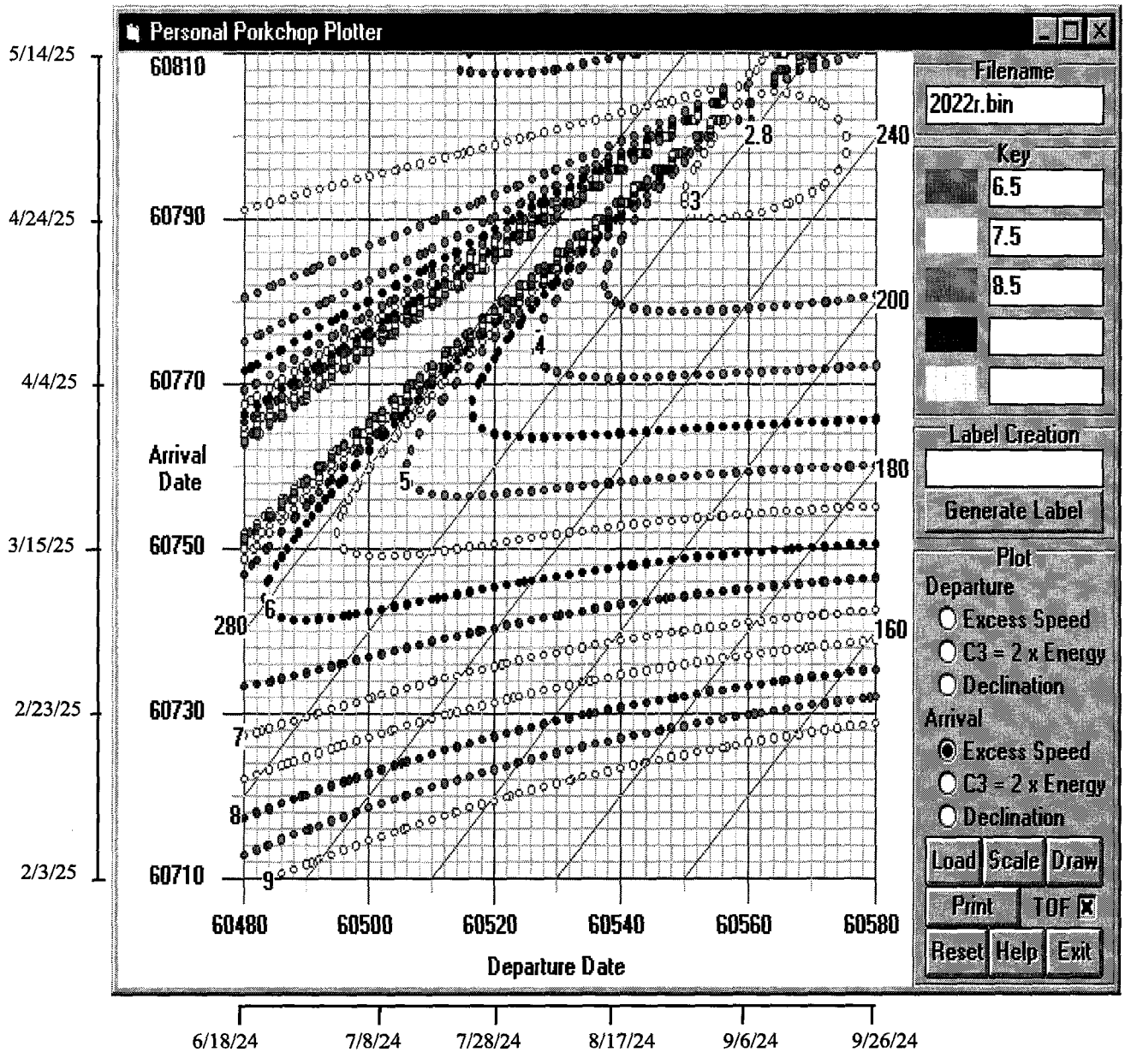
Mars-Earth Trajectories
2024 Conjunction Class
(Returns from 2022 Missions)
Departure Excess Speed (km/sec)



Mars-Earth Trajectories
2024 Conjunction Class
(Returns from 2022 Missions)
Arrival Declinations (degrees)



Mars-Earth Trajectories
2024 Conjunction Class
(Returns from 2022 Missions)
Arrival Excess Speed (km/sec)



Mars-Earth Trajectories
2024 Conjunction Class
(Returns from 2022 Missions)
Arrival Declination (Degrees)

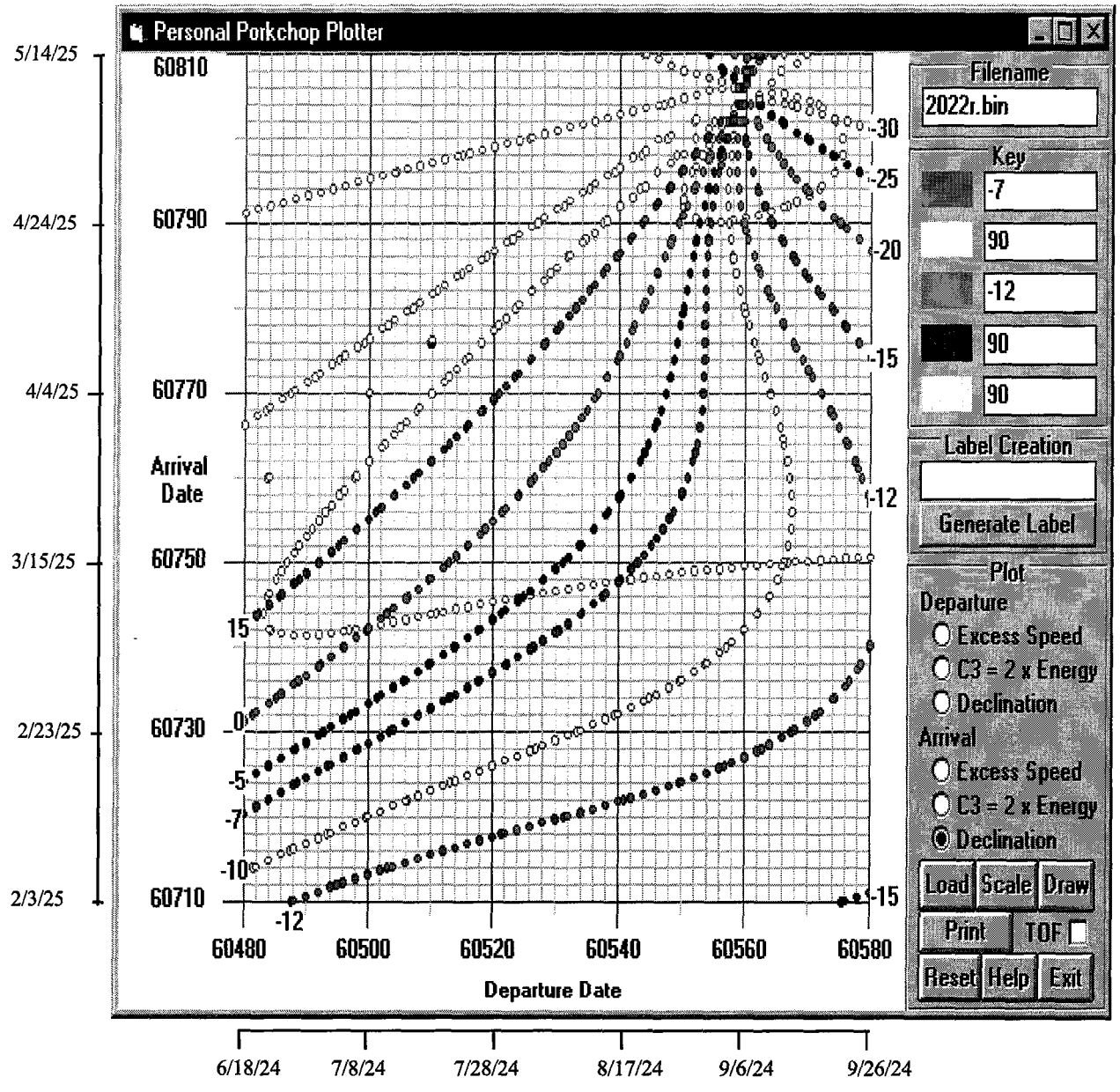
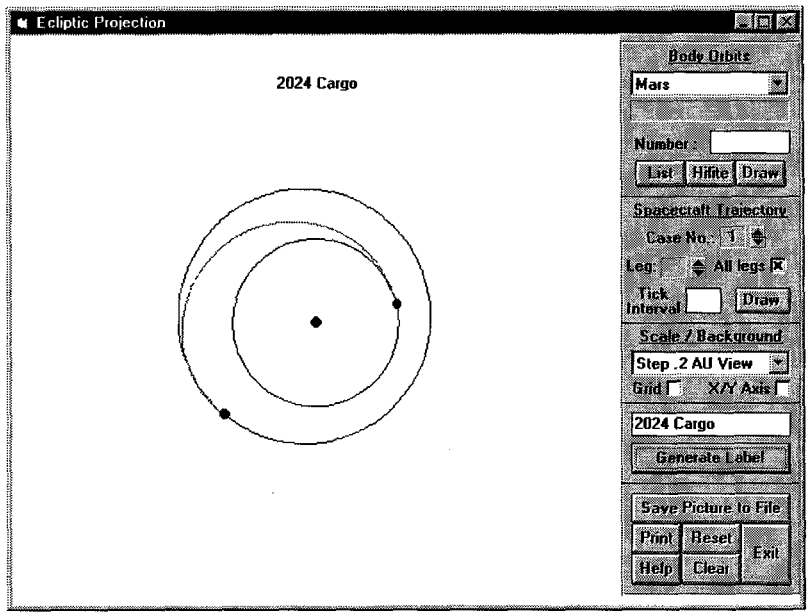
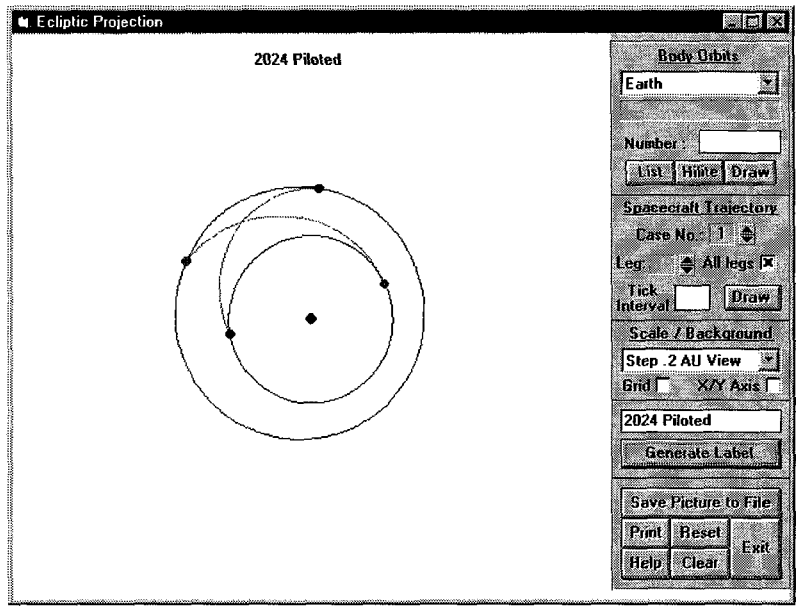


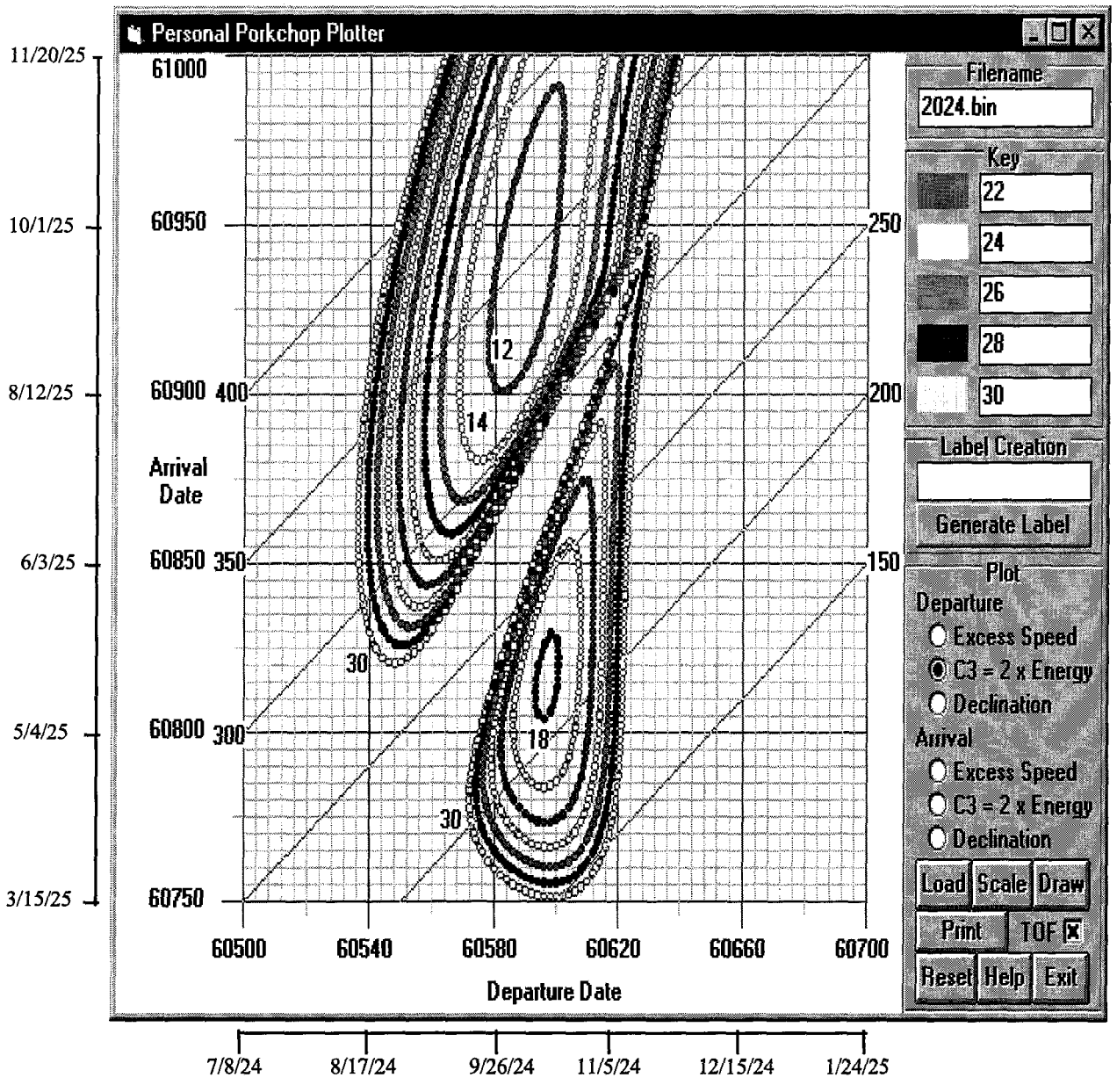
Table 16. 2024 opportunities summary.

Mission Type	TMI Date (m/d/yy)	TMI ΔV (m/s)	Velocity Losses (m/s)	Mars Arrival Date (m/d/yy)	Outbound Flight Time (days)	Mars Stay Time (days)	Mars Departure Date (m/d/yy)	TEI ΔV (m/s)	Return Time (days)	Return Date (m/d/yy)	Total Mission Duration (days)	C_3 (km/sec)	Total ΔV (m/sec)	Depart. V_∞ Earth (km/sec)	Arrival V_∞ Mars (km/sec)	Arrival Velocity @ Mars (km/sec)	Depart. V_∞ Mars (km/s)	Arrival V_∞ Earth (km/s)	Arrival Velocity @ Earth (km/s)
Cargo 1	10/5/24	3,782	101	9/15/25	345	—	—	—	—	—	—	11.19	3,782	3.3452	2.541	5.548	—	—	—
Cargo 2	10/5/24	3,805	124	9/15/25	345	—	—	—	—	—	—	11.19	3,805	3.3451	2.541	5.548	—	—	—
Piloted	10/17/24	4,257	158	4/15/25	180	535	10/2/26	1,841	180	3/31/27	895	20.85	6,098	4.5657	6.09	7.837	4.251	9.248	10.48

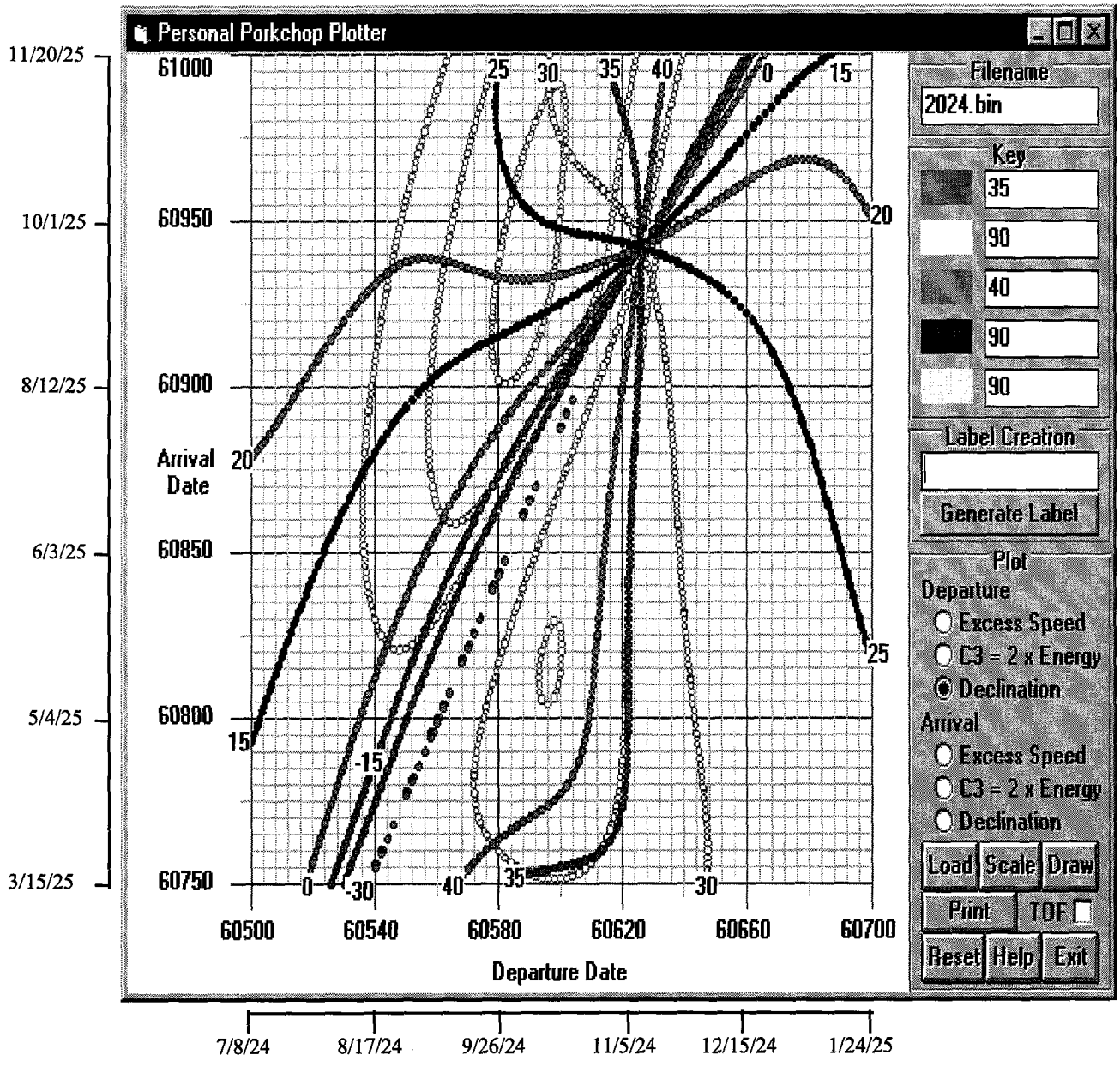




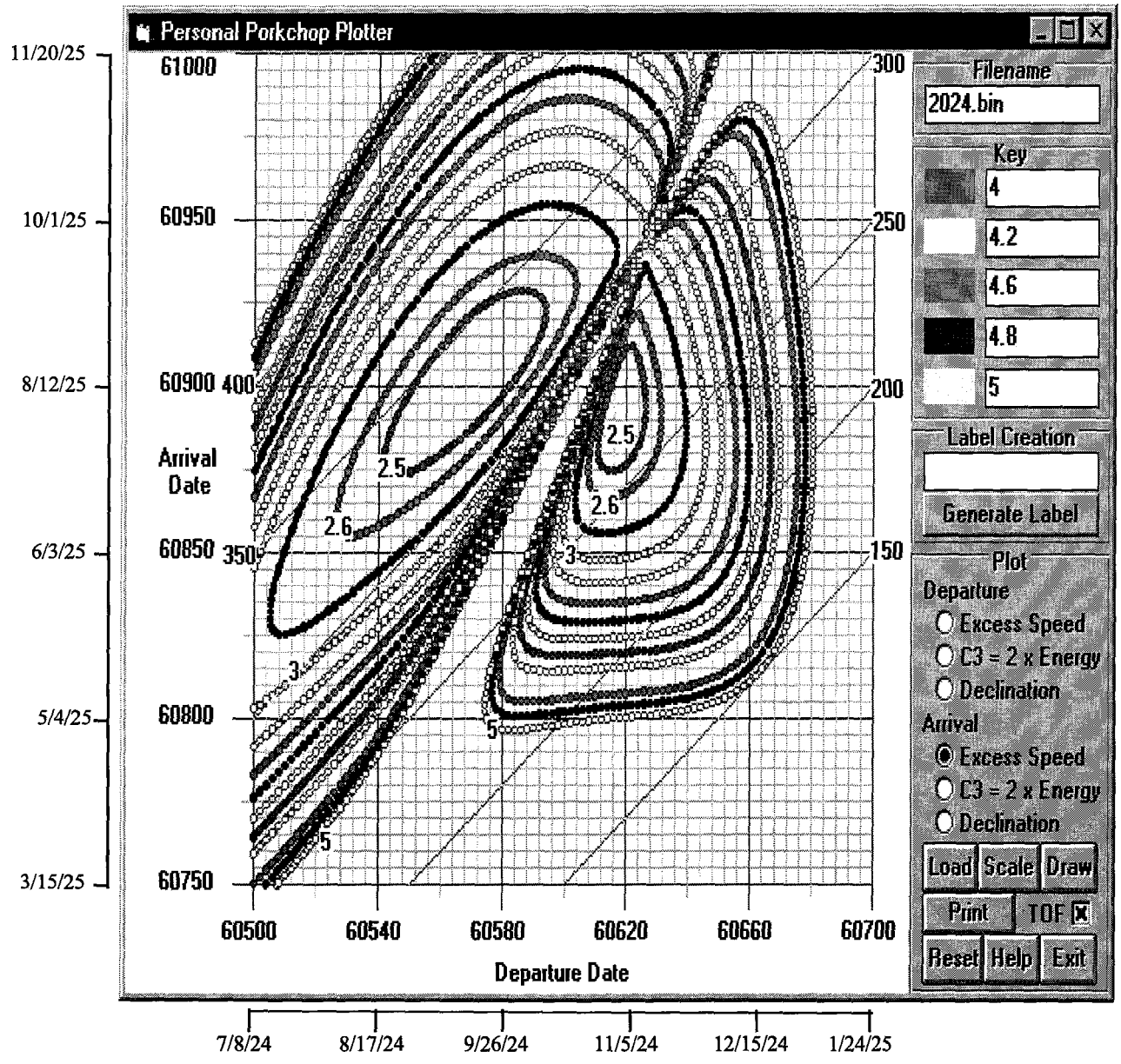
Earth-Mars Trajectories
2024 Conjunction Class
C_3 Departure Energy (km^2/sec^2)



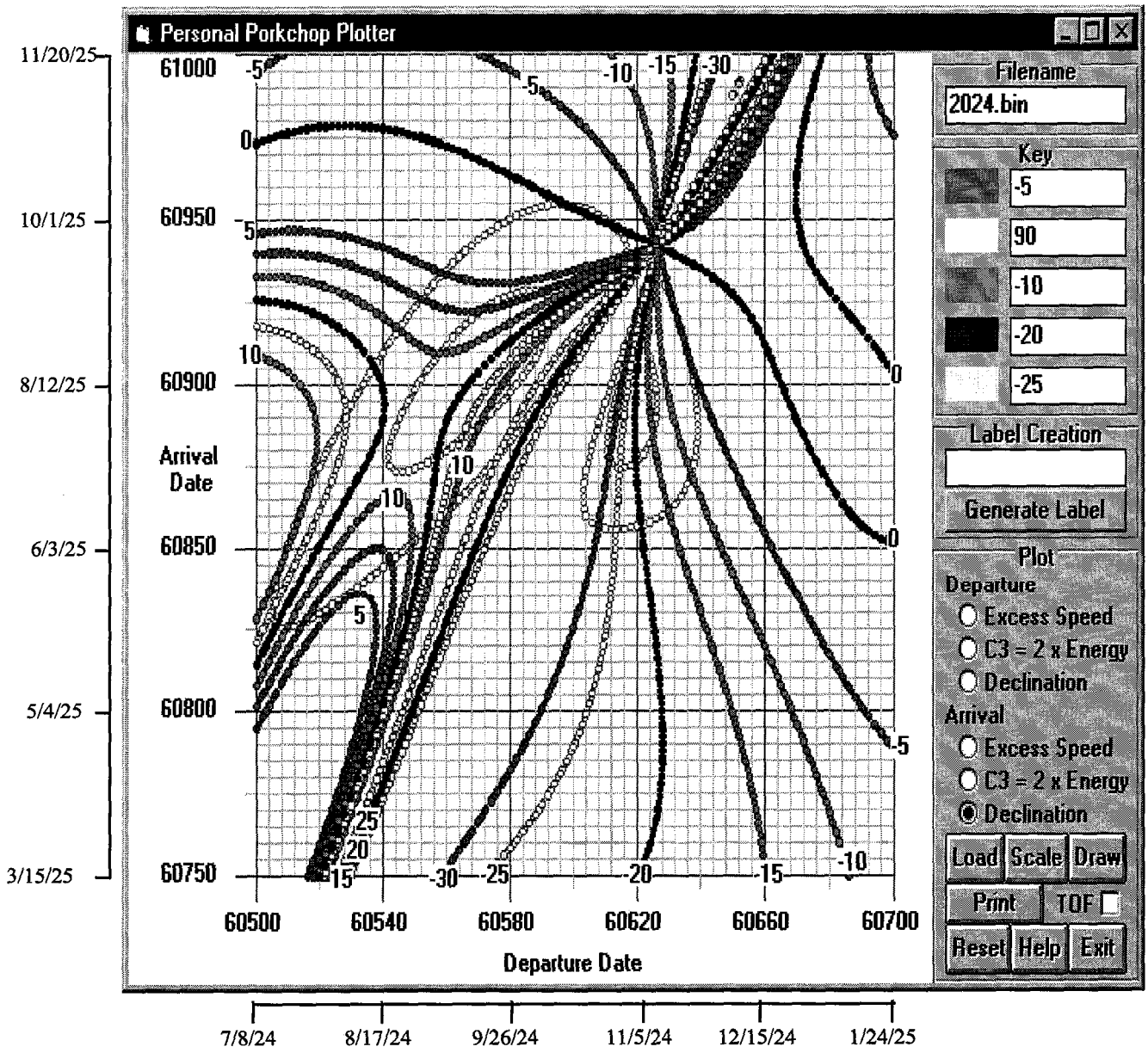
Earth-Mars Trajectories
2024 Conjunction Class
Departure Declination (Degrees)



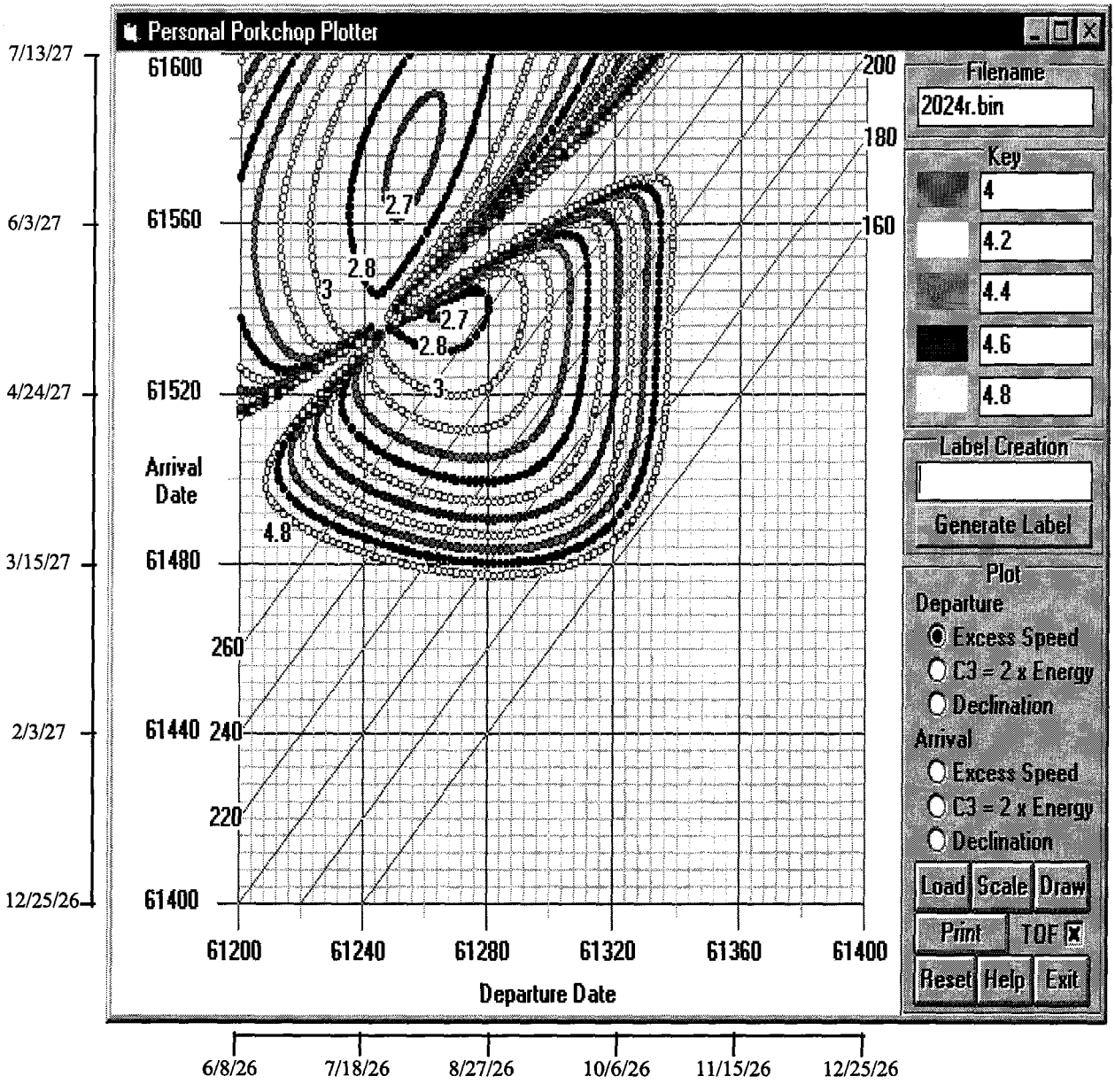
Earth-Mars Trajectories
2024 Conjunction Class
Arrival Excess Speed (km/sec)



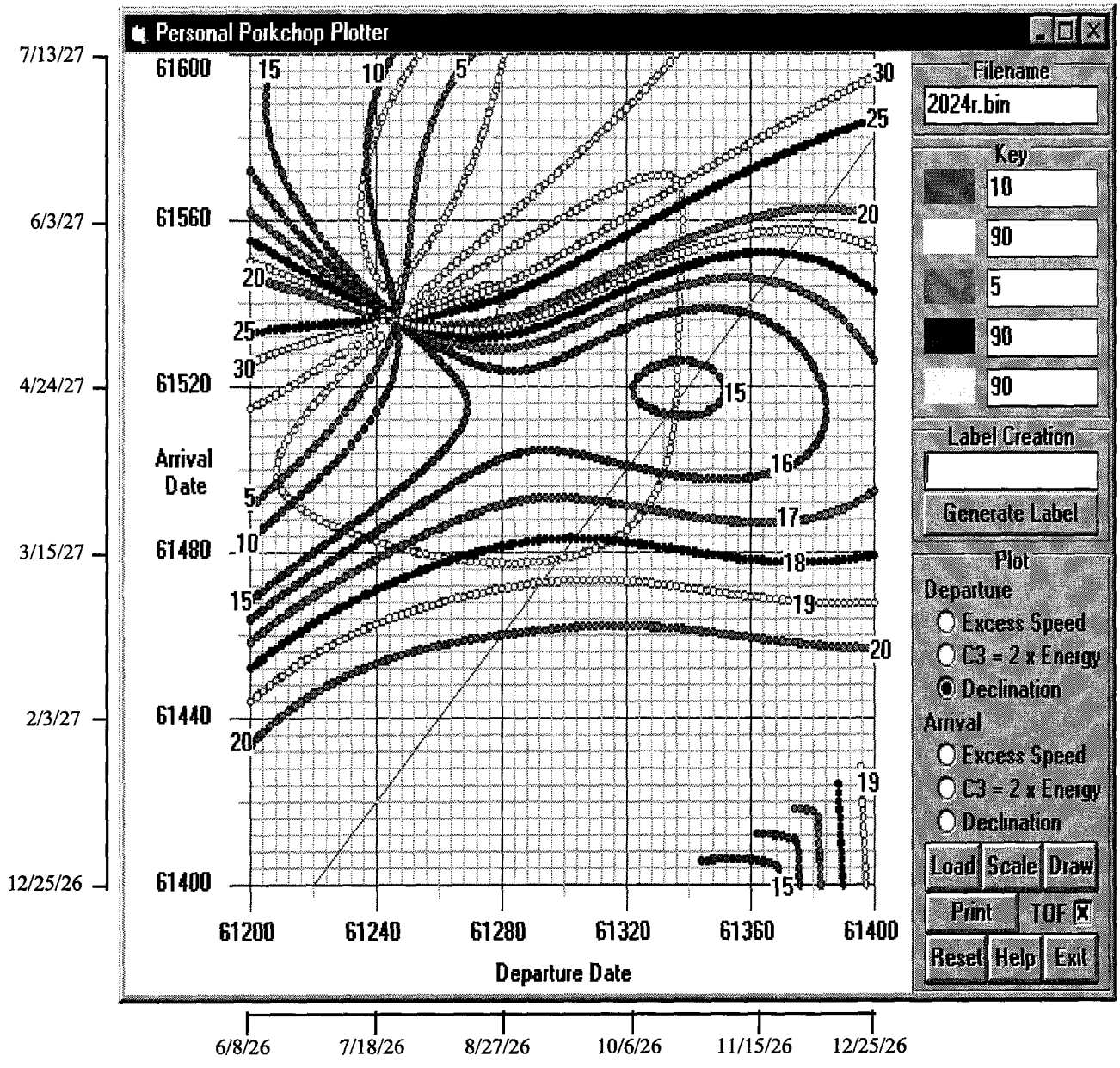
Earth-Mars Trajectories
2024 Conjunction Class
Arrival Declination (Degrees)



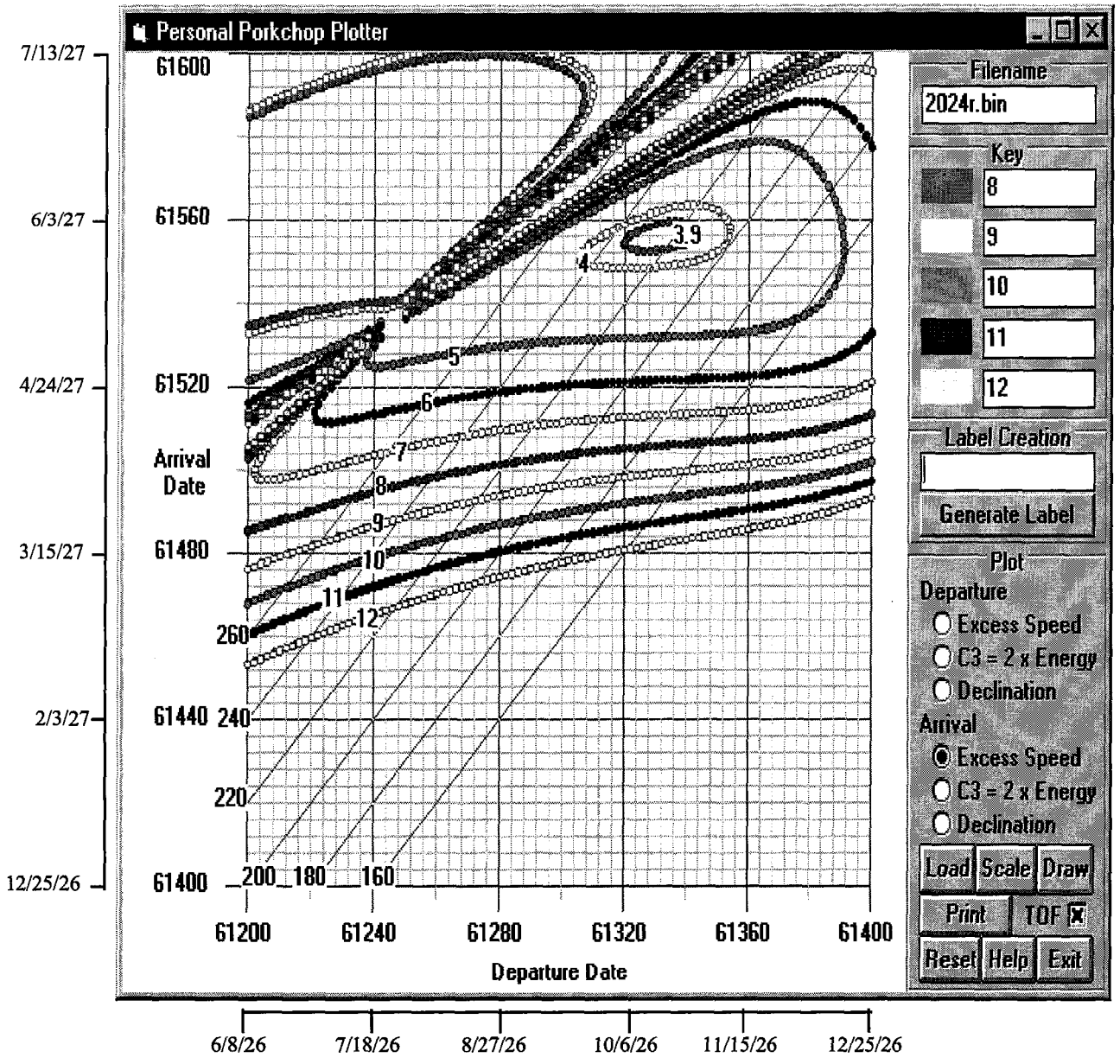
Mars-Earth Trajectories
2026 Conjunction Class
(Returns from 2024 Missions)
Departure Excess Speed (km/sec)



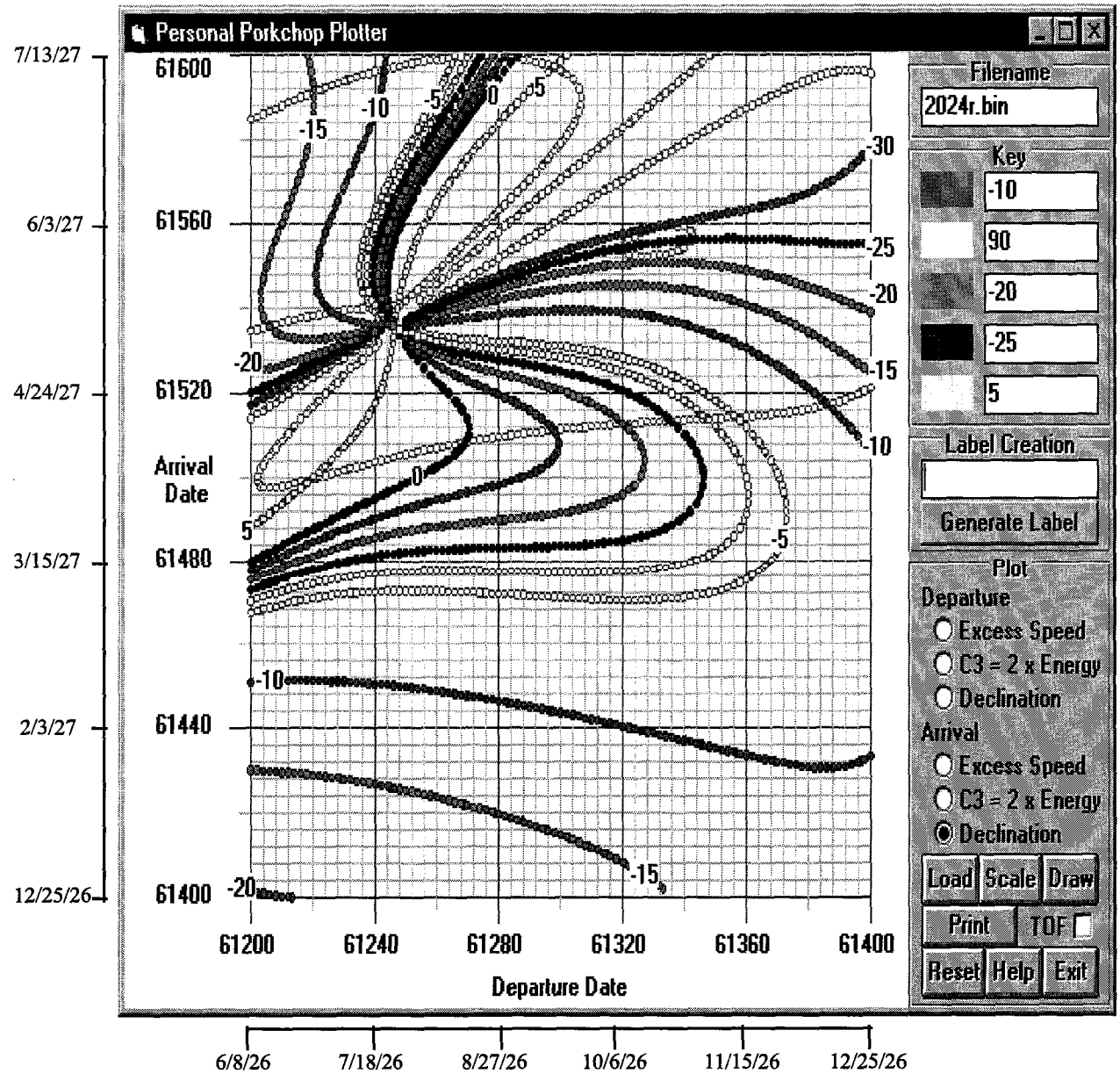
Mars-Earth Trajectories
2026 Conjunction Class
(Returns from 2024 Missions)
Departure Declinations (degrees)



Mars-Earth Trajectories
2026 Conjunction Class
(Returns from 2024 Missions)
Arrival Excess Speed (km/sec)



Mars-Earth Trajectories
2026 Conjunction Class
(Returns from 2024 Missions)
Arrival Declinations (Degrees)



APPENDIX B—FREE-RETURN TRAJECTORIES

For each opportunity, there exists a trajectory that will allow a "free return" in case of abort on the outbound trip.[10] These may become important if it is deemed necessary to keep open the opportunity to abort in case of a problem enroute. Instead of normal capture at Mars, a swingby would be performed and the payload would immediately begin its return to Earth. Assuming there would be no fuel available (i.e., some problem in route with the descent vehicle), the only way for the crew to get back to Earth would be to perform a swingby of Mars. There supposedly are 2-year free-return trajectories available; however, all of the ones derived from MAnE trajectories resulted in unacceptable Mars aerobraking entry velocities. The only trajectories that resulted in low enough entry velocities much longer return trip times (2 1/2 yrs) and higher departure velocities. All of the free return trajectories are summarized in table 11. Note that the ΔVs do not include velocity losses.

Table 17. Free return trajectories.

Launch Year	TMI Date (m/d/yr)	TMI ΔV (m/sec)	Mars Arrival Date (m/d/yr)	Outbound Flight Time (days)	Return Time (days)	Return Date (m/d/yr)	Total Mission Duration (days)	C_3 (km^2/sec^2)	Departure V_∞ @ Earth (km/sec)	Arrival V_∞ @ Mars (km/sec)	Arrival Velocity @ Mars (km/sec)	Arrival V_∞ @ Earth (km/sec)	Arrival Velocity @ Earth (km/sec)
2009	11/13/09	4,255	5/12/10	180	780	6/30/12	960	24.55	4.955	5.661	7.508	9.360	14.498
2009*	11/2/09	4,535	3/28/10	146	533	9/12/11	679	31.31	5.595	9.478	10.684	8.998	14.267
2011	12/2/11	3,887	5/30/12	180	832	9/9/14	1,012	15.92	3.989	7.073	8.623	8.451	13.928
2013**	11/5/13	5,392	5/20/14	196	596	1/6/16	792	52.98	7.279	9.239	10.472	5.045	12.167
2013	12/30/13	3,692	6/28/14	180	889	12/3/16	1,069	11.45	3.383	7.167	8.700	4.237	11.855
2014	1/20/14	3,887	6/30/14	161	889	12/5/16	1,050	15.92	3.989	7.167	8.700	4.169	11.831
2016**	1/2/16	4,596	6/27/16	177	612	3/1/18	789	32.82	5.729	9.217	10.453	5.060	12.173
2016	1/17/16	4,037	7/15/16	180	1,099	7/19/19	1,279	19.41	4.406	7.770	9.203	3.441	11.594
2018	5/20/18	3,887	9/13/18	116	931	4/1/21	1,047	15.92	3.989	6.651	8.280	4.890	6.945
2020	7/15/20	3,887	12/18/20	156	877	5/14/23	1,033	15.92	3.989	4.320	6.556	7.176	8.707
2020/opt	7/19/20	3,665	1/15/21	180	943	8/16/23	1,123	13.43	3.665	3.154	5.854	4.988	7.0146
2022	9/10/22	4,047	3/9/23	180	962	10/26/25	1,142	19.63	4.431	4.621	6.758	9.083	10.335
2024	10/25/24	4,157	4/23/25	180	954	12/3/27	1,134	22.23	4.715	5.644	7.495	9.360	10.580

APPENDIX C—ASSUMPTIONS

These following assumptions came from information provided by the author Larry Kos and reference 11.

General

Earth Departure

These assumptions are used for both the cargo and piloted missions. The only difference will be the desired payload left at Mars. It is assumed that the TMI stages are initially assembled and launched from a 400-km circular parking orbit at an inclination of approximately 28.5°. There will be two perigee burns upon departure. The second burn will transfer the rocket into a hyperbolic escape orbit and on the transfer to Mars. The TMI stage will be a nuclear thermal propulsion system (LH_2) with a specific impulse of 931 sec. (Nuclear propulsion system I_{sp} is approximately 960 sec minus 3 percent to account for reactor cool-down losses) and a T/W ratio of approximately 0.14 (will vary depending on the total stack masses for the particular mission). It will consist of three 15,000 lb_f thrust engines. Dry weight of the stage/engine assembly is approximately 25.7 mt. The stage will be jettisoned immediately after second perigee burn. A mid-course targeting correction ΔV of 50 m/sec is assumed but not included in these calculations.

Mars Arrival

The resulting parking orbit at Mars will be a 1-solar-day orbit of 250-km perigee × 33,793-km apogee (eccentricity, $e = 0.8214$) and inclination of approximately 40°. The landing site latitude is assumed to be approximately 30° North. The maximum allowable entry speed at Mars for aerobraking is 8.7 km/sec (inertial). This corresponds to a limit at V_∞ of 7.167 km/sec at Mars using equation (1) at the conventional entry altitude of 125 km.

Mars Departure

Departure is from 250-km perigee orbit ($e = 0.8214$). One burn is performed and the TEI stage is jettisoned after maneuver except for the RCS which is used for the transfer back to Earth. The TEI stage I_{sp} is 379 sec with a T/W ratio of 0.2387 and a dry weight of 3.57 mt (not including RCS).

Earth Arrival

Near-ballistic entry limit (inertial) at Earth is 14.5 km/sec. This corresponds to a limit on V_∞ of 9.36 km/sec calculated using equation (2) at an assumed entry altitude of 125 km.

Mission Specific Assumptions and Mass Properties

Cargo 1 Mission

T/W ratio: 0.14915
- Thrust: 45,000 lb_f
- Weight: 136.9 mt

Payload and parameters:
- Return habitat: 21.62 mt
- RCS: 1.1 mt
- TEI burnout mass: 3.57 mt
- TEI propellant: 31.3 mt (includes boil-off losses)

Total cargo 1: 61.67 mt
Engine mass: 22.42 mt
Aerobrake: 10.6 mt

Cargo 2 Mission

T/W ratio: 0.1354
- Thrust: 45,000 lb_f
- Weight: 150.8 mt

Payload and parameters:
- Return capsule: 5.5 mt
- Descent stage: 4.19 mt
- Stage propellant: 17.1 mt

Total cargo 2: 61.89 mt
Engine mass: 22.42 mt
Aerobrake: 15.99 mt

Piloted Mission Outbound

Outbound T/W ratio: 0.1434
- Thrust: 45,000 lb_f
- Weight: 142.4 mt

Payload and parameters:
- Surface habitat: 18.47 mt (not including EVA's)
- Surface payload: 9.8 mt
- Descent stage: 4.19 mt
- Propellant: 17.3 mt

Total payload left at Mars: 49.76 mt
Engine mass: 25.7 mt (note this includes a 3.2 mt shield)
Aerobrake: 14.04 mt
Inert mass: 1.3 mt (crew 0.5 mt + EVA's 0.8 mt)

Piloted Mission Return

Inbound T/W ratio: 0.2388
- Thrust: 30,000 lb_f
- Weight: 57.01 mt

Payload and Parameters:
- Return capsule: 5.5 mt
- Return payload: 0.125 mt

Total payload to return to Earth: 5.6 mt
- Return RCS: 1.1 mt
- Return shielding: 11.28 mt
- Return habitat: 15.02 mt (assume 500 days of contingency consumables dropped at Mars)

Inert mass: 1.3 mt (crew and EVA's)

Engine mass: 3.57 mt

APPENDIX D—OVERVIEW OF MAnE

The MAnE component that performs trajectory optimization is HIHTOP.[3] HIHTOP is designed to identify optimal missions with respect to required criterion and subject to the satisfaction of specified constraints and end conditions. For more information on HIHTOP capabilities, see reference 3.

In this handbook, optimum missions were those based on minimum initial masses required in low-Earth and Mars departure orbits. The cargo missions were constrained only by the payload delivery requirements (Cargo 1—61.67 mt, Cargo 2—61.89 mt) as listed in the appendix C—Assumptions. The program then varied departure dates, arrival dates, and initial mass to determine the trajectory that would allow minimum initial mass. The piloted mission was constrained by the payload delivery requirements (outbound—49.68 mt plus 1.3 mt, return—5.625 mt plus 1.3 mt), an in-flight time for each leg of 180 days, and a maximum V_∞ allowed at Earth and Mars to stay within aerobraking and Earth ballistic reentry limits.

MAnE allows for detailed modeling of all propulsion system characteristics and the mass composition of the spacecraft. The following were used as the baseline mass and propulsion system models for these trajectories:

Cargo 1:
- Departure I_{sp}: 931 sec
- T/W ratio: 0.1417
- Engine mass: 22.42 mt
- Total cargo delivered to Mars: 61.67 mt (specified as a required end condition)
- Aerobrake mass: 11.28 mt

Cargo 2:
- Departure I_{sp}: 931 sec
- T/W ratio: 0.1441
- Engine mass: 22.42 mt
- Total cargo delivered to Mars: 61.89 mt
- Aerobrake: 15.99 mt

Piloted Mission Outbound:
- Departure specific impulse: 931
- T/W ratio: 0.1441
- Engine mass: 25.17 mt
- Total payload left on Mars: 49.68 mt
- Aerobrake: 14.04 mt
- Inert mass: 1.3 mt (crew 0.5 mt + EVA's 0.8 mt)

Piloted Mission return:

I_{sp}: 379 sec
T/W ratio: 0.2387
Engine mass: 3.57 mt
Total payload to return to Earth: 5.63 mt
Inert mass: 1.3 mt (crew and extravehicular activities)

The conic sections that represent the Earth/Mars and Mars/Earth trajectories are evaluated by MAnE by solving Lambert's problem for given initial and final position vectors and transfer times. This solution will yield the heliocentric velocity vectors at the departure and arrival points. From Lambert's Theorem for two-body motion, there exist two unique trajectories—one posigrade and one retrograde—connecting two points in space at any given time with a transfer angle less than 360° (posigrade heliocentric motion is defined as counter-clockwise motion when viewed from a point above the ecliptic plane, or in the direction of planetary motion about the Sun). All transfers analyzed in this study were posigrade. The orbit injection model assumed injection takes plane at the common periapse of the departure parking orbit and the hyperbolic escape trajectory.

Velocity losses are defined as the difference in the integral of the thrust acceleration magnitude over the duration of the maneuver and the impulsive requirement ΔV. MAnE provides the capability to include an estimate of velocity losses that would be encountered performing planetary escapes. The methodology is based on the vehicle's propellant mass ratio, jet exhaust speed, thrust, and initial masses. For more information about this, see reference 5. A key point here, though, is in determining the intermediate orbit. Instead of attempting complete analytical optimizations of the sequence of orbits, it is assumed that the duration of the individual burns is nearly equal. This was a conclusion derived from a review of the Robbins method. This may explain differences between MAnE solutions and other references available.

The MAnE trajectory mapper utility allows the user to generate a matrix of single-leg trajectories at constant intervals of departure and arrival dates. Departure and arrival dates were chosen to characterize the mission opportunity areas of interest.

The orbital elements of the planets vary with time, so the standard reference used in MAnE were those given as of January 24, 1991 (J2000), with updates provided. Since the sizes, shapes, and locations of the planetary orbits change over time, the ephemeris calculations are updated to the current year. The osculating elements are maintained as cubic polynomials in J2000.

The "porkchop" visualization utility quickly creates contour charts of selected parameters for any single-leg mission that MAnE is capable of mapping. The program uses as the input the binary file created with the companion utility Trajectory Mapper.

Independent parameters used included:

- Times of departure and arrival
- Initial spacecraft mass (initial T/W ratios could be, but they were set as constants).

End conditions may include:

- Flight times of individual legs (180 days used for piloted missions)
- Mission duration (used for 360-day total TOF studies)
- Departure hyperbolic excess speed (used to evaluate piloted missions at 2011 C_3s)
- Arrival hyperbolic excess speed (to limit Mars or Earth entry velocities if exceeded with optimal solution)
- Swingby passage distance (used for free-returns to ensure minimum periapse distance at Mars was not less than 1)
- Net spacecraft mass (used to deliver applicable payload mass to Earth and Mars).

Optimization criteria were available to minimize:

- Initial spacecraft mass—used for all cargo missions and some piloted transfers
- Sum of propulsion ΔVs—used for free return trajectories
- Mission duration—used to minimize piloted mission durations to 2011 C_3s (net spacecraft mass also available).

APPENDIX E—FLIGHT TIME STUDIES

First, the 2011 conjunction piloted missions were evaluated by optimizing trajectories at outbound legs longer than 180 days and return legs shorter than 180 days. The total flight time was kept at 360 days (i.e., 178 out/182 return). Table 18 summarizes the results for 2011. The only constraints imposed were on total flight time and the constraint to keep payload weights less than 80 mt. For the shorter legs outbound, 158 days was the minimum amount that would allow an acceptable TMI stage mass. For the shorter legs inbound, 162 days was found to be the minimum, at which point the TEI stage mass would be excessive. However, with the shorter outbound leg trips it was found that V_∞ limits at Mars would be excessive for aerobraking limits, and for short return legs the V_∞ limit at Earth would be excessive for allowable reentry limits.

The conclusion from the 2011 studies is that the maximum benefit comes with shortening the outbound leg (increasing slightly the TMI propellant used) but lengthening the inbound leg. The overall result is a decrease in both the TEI piloted stage mass required and the cargo 1 initial mass in LEO. However, with the shorter leg trips the incoming velocities are excessive and must be closely monitored to prevent exceeding design specifications.

The 2011 study provided a starting point for the baseline 2014 mission studies. The method used to evaluate the 2014 opportunity is summarized in figure 10. It was assumed that to minimize total mission cost one would want to minimize initial masses of both the cargo 1 mission and the outbound piloted mission. Table 19 provides more detailed information about the reduction in propellant loading required for each individual mission in case a specific leg or mission was deemed more critical than another.

To interpret the data in this plot, first, notice the optimal point marked with a bold **o.** This is the point associated with the minimum passage time associated with the 2011 C_3s. Note the region with an outbound TOF less than 161 days will result in an excessive Mars entry velocity. By lengthening the return TOF, the required initial mass in Mars departure orbit will be reduced, which in turn reduces the required initial mass for the cargo 1 mission. In addition, by lengthening the outbound TOF, the required initial mass in LEO for the outbound piloted mission was reduced. The greatest reduction was at data points along the 360-day TOF line. What is not so obvious is at which particular point along the diagonal TOF lines the maximum reduction occurs. For the 360-day TOF line, several points were chosen along this line and it was found that the optimal point is at 171 days outbound and 189 days return.

Table 18. 2011 TOF trades.

TOF Out	TMI Prop	Earth M_{init}	Prop Added	TMI Mass	TOF Return	TEI Prop	Prop Added	Delta Total	Cargo1 Del	Cargo1 M_{init}	TEI Mass	Min - Nom
Baseline trajectory												
180	**50.13**	**140.80**	**0.00**	**75.78**	**180**	**18.47**	**0.00**	**0.00**	**61.67**	**143.78**	**73.00**	**0.00**
Unavailable options because piloted TMI stage > 80 mt												
150	56.18	146.85	6.05	81.83	210	12.74	–5.74	0.31	55.93	135.13	67.26	–2.60
152	55.61	146.28	5.48	81.26	208	13.00	–5.47	0.01	56.20	135.54	67.53	–2.77
154	55.06	145.74	4.94	80.72	206	13.29	–5.19	–0.25	56.48	135.96	67.81	–2.88
156	54.55	145.23	4.43	80.21	204	13.58	–4.89	–0.46	56.77	136.41	68.11	–2.95
Unavailable options because entry velocity at Mars exceeded:												
158	54.07	144.77	3.95	79.73	202	13.89	–4.58	–0.64	57.08	136.88	68.42	–2.96
160	53.61	144.29	3.49	79.27	200	14.22	–4.26	–0.77	57.41	137.37	68.74	–2.93
162	53.12	143.79	2.99	78.77	198	14.56	–3.92	–0.93	57.75	137.88	69.08	–2.91
164	52.77	143.44	2.64	78.42	196	14.91	–3.56	–0.92	58.11	138.42	69.44	–2.73
166	52.37	143.05	2.25	78.03	194	15.29	–3.19	–0.94	58.48	138.98	69.81	–2.55
168	52.00	142.68	1.88	77.66	192	15.68	–2.79	–0.92	58.87	139.57	70.21	–2.33
170	51.65	142.33	1.52	77.31	190	16.09	–2.38	–0.86	59.28	140.19	70.62	–2.07
172	51.31	141.99	1.19	76.97	188	16.52	–1.95	–0.76	59.71	140.84	71.05	–1.76
174	50.99	141.67	0.87	76.65	186	16.98	–1.50	–0.63	60.17	141.52	71.50	–1.39
176	50.69	141.37	0.56	76.35	184	17.45	–1.02	–0.46	60.64	142.24	71.98	–0.98
178[1]	50.40	141.08	0.28	76.06	182	17.95	–0.52	–0.25	61.14	142.99	72.48	–0.51
Unavailable options because entry velocity at Earth exceeded:												
182[2]	49.86	140.54	–0.26	75.52	178	19.03	0.55	0.29	62.22	144.62	73.55	0.57
184	49.61	140.29	–0.51	75.27	176	19.61	1.13	0.62	62.80	145.49	74.13	1.19
186	49.37	140.05	–0.75	75.03	174	20.22	1.74	0.99	63.41	146.41	74.74	1.88
188	49.14	139.82	–0.98	74.80	172	20.86	2.39	1.41	64.05	147.38	75.39	2.62
190	48.93	139.60	–1.20	74.58	170	21.54	3.07	1.87	64.73	148.41	76.07	3.42
192	48.72	139.39	–1.41	74.37	168	22.26	3.78	2.37	65.45	149.48	76.78	4.29
194	48.52	139.20	–1.61	74.18	166	23.01	4.54	2.93	66.20	150.62	77.54	5.23
196	48.33	139.00	–1.80	73.98	164	23.81	5.33	3.54	67.00	151.82	78.33	6.24
198	48.15	138.82	–1.98	73.80	162	24.65	6.18	4.20	67.84	153.09	79.18	7.33
Unavailable options because Cargo 1 stack with TEI stage mass > 80 mt												
200	47.97	138.65	–2.15	73.63	160	25.54	7.07	4.91	68.73	154.44	80.07	8.50
202	47.81	138.48	–2.32	73.46	158	26.48	8.01	5.69	69.68	155.86	81.01	9.76
204	47.67	138.32	–2.48	73.30	156	27.48	9.01	6.53	70.68	157.37	82.01	11.10
206	47.49	138.17	–2.63	73.15	154	28.54	10.07	7.44	71.74	158.96	83.07	12.55
208	47.37	138.02	–2.78	73.00	152	29.67	11.19	8.42	72.86	160.66	84.19	14.10
210	47.21	137.88	–2.92	72.86	150	30.86	12.39	9.47	74.06	162.46	85.39	15.76

Note: These trades were performed using older, more conservative masses for the Cargo 1 and Piloted missions;
(1) Arrival entry velocity at Mars = 7.202 km/sec (exceeds limit of 7.167 km/sec).
(2) Arrival entry velocity at Earth = 9.44 km/sec (exceeds limit of 9.36 km/sec).

Table 19. 2014 TOF trades.

TOF Outbound (days)[1]	Dep Date (m/d/yr)	TMI Prop Required (mt)	Earth $M_{initial}$ (mt)[2]	Prop Redn (mt)[3]	Total TMI Mass (mt)[4]	TOF Inbound (days)	Dep Date (m/d/yr)	Total TOF (days)	TEI Prop Required (mt)	Prop Redn (mt)[5]	Cargo 1 Delivery (mt)[6]	Cargo 1 $M_{initial}$ (mt)	Total Init Mass (mt)[7]	Total Delta
161	**1/20/14**	**50.43**	**141.19**	**0.00**	**76.09**	**154**	**1/24/16**	**315**	**18.39**	**0.00**	**57.59**	**135.48**	**276.67**	**0.00**
161	1/20/14	50.43	141.19	0.00	76.09	160	1/20/16	321	16.68	–1.71	55.88	132.80	273.99	–2.67
161	1/20/14	50.43	141.19	0.00	76.09	170	1/14/16	331	14.42	–3.97	53.62	129.42	270.61	–6.06
171	1/9/14	47.62	138.38	–2.81	73.27	160	1/20/16	331	16.68	–1.71	55.88	132.80	271.17	–5.50
165	1/16/14	49.02	139.78	–1.41	74.67	175	1/11/16	340	13.50	–4.88	52.71	128.21	267.98	–8.69
170	1/10/14	47.80	138.56	–2.63	73.45	170	1/14/16	340	14.42	–3.97	53.62	129.58	268.14	–8.54
175	1/6/14	47.10	137.86	–3.33	72.75	165	1/17/16	340	15.47	–2.91	54.68	131.15	269.01	–7.66
161	1/20/14	50.43	141.19	0.00	76.09	180	1/7/16	341	12.70	–5.69	51.90	126.85	268.04	–8.63
161	1/20/14	50.43	141.19	0.00	76.09	190	1/1/16	351	11.38	–7.00	50.59	124.88	266.07	–10.61
161	1/20/14	50.43	141.19	0.00	76.09	199	12/27/15	360	10.47	–7.92	49.67	123.51	264.70	–11.97
175	1/6/14	47.10	137.86	–3.33	72.75	185	1/4/16	360	12.00	–6.39	51.20	125.96	263.81	–12.86
180	1/4/14	46.60	137.36	–3.83	72.25	180	1/7/16	360	12.70	–5.67	51.90	127.01	264.36	–12.31
185	1/3/14	46.17	136.93	–4.26	71.82	175	1/11/16	360	13.50	–4.88	52.71	128.21	265.14	–11.54
163	1/18/14	49.67	140.43	–0.76	75.33	197	12/28/15	360	10.65	–7.73	49.86	123.92	264.35	–12.32
165	1/16/14	49.02	139.78	–1.41	74.67	195	12/29/15	360	10.85	–7.54	50.05	124.21	263.98	–12.69
167	1/14/14	48.46	139.22	–1.97	74.12	193	12/30/15	360	11.05	–7.34	50.25	124.51	263.73	–12.94
169	1/12/14	48.00	138.76	–2.43	73.65	191	1/1/16	360	11.27	–7.12	50.47	124.84	263.60	–13.08
171	1/9/14	47.62	138.38	–2.81	73.27	189	1/2/16	360	11.50	–6.89	50.70	125.18	263.56	–13.11
173	1/7/14	47.32	138.08	–3.11	72.98	187	1/3/16	360	11.74	–6.65	50.94	125.55	263.63	–13.04

Notes:

(1) Italicized trajectories have a constraint that the arrival velocity at Mars = 7.167 km/sec (otherwise would be greater)

(2) $M_{initial}$ for piloted outbound = 90.76 mt + TMI propellant required (from MAnE run for baseline trajectory)

(3) Propellant reduction for Mars outbound = 50.43–propellant required (from MAnE run for baseline trajectory)

(4) Total TMI mass = 25.6 mt (dry weight of TMI engine) + propellant required

(5) Propellant reduction for Earth return flight = 18.386–propellant required (from MAnE run for baseline trajectory)

(6) *Cargo 1 delivery required = Total payload delivery to Mars (57.59 mt)–propellant reduction*

(7) Total departure initial mass in LEO = piloted outbound + cargo 1 missions.

APPENDIX F—GRAVITY LOSS STUDIES

A short side-study was performed to assess the effect of various T/W ratios on gravity losses at Earth. The larger the T/W ratio, the lower the effect of gravity losses. The gravity losses were determined from MAnE runs for the following configurations:

T/W = 0.12 (envelope heaviest possible stack)
T/W = 0.135
T/W = 0.149
T/W = 0.2 (approximately the effect of adding a third engine).

In addition, the effect of the following was looked at for the 2011 C_3s:

(1) 2 burns/4 engines (increases T/W to 0.2 and adds 2 mt to the engine weight)
(2) 3 burns/3 engines
(3) 3 burns/4 engines.

As expected, case (1) should fall closely in line with the T/W=0.2 case (the exception being the actual added engine weight, which is a minimal effect). Also as expected, with an additional burn the gravity losses are reduced. The tradeoff is the longer in-flight time the crew would need to endure. According to the MAnE results, this would involve a coast period prior to the third burn of approximately 8 hours. The other choice would be to add an additional engine to reduce gravity losses.

APPENDIX G—VERIFICATION OF MAnE RESULTS

Two methods were used to verify MAnE results. First, a number of trajectories from 2001–2020 were verified and comparisons of ΔV were made. All results were consistent with previous tools used. For these verifications, assumed launch and arrival times are at 1200 GMT on the day indicated. These verifications are summarized in table 20.

In addition, plots for 2005 departure, 2006, and 2004 return opportunities were generated using MAnE and compared with references 7 and 9.

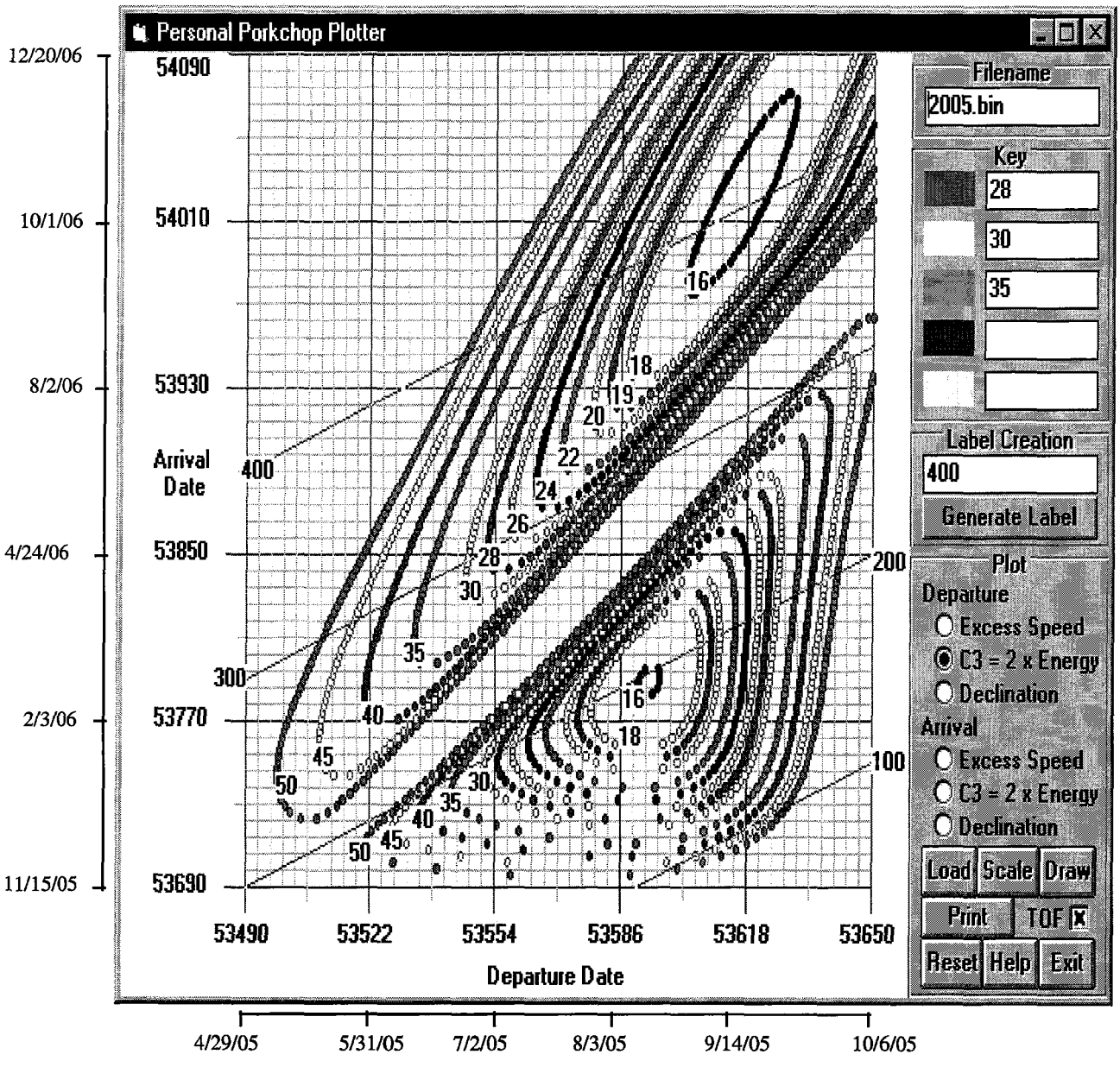
The 2004 and 2006 return opportunities generated in MAnE follow along with their associated plots from reference 8. When comparing the two, note the reversal of the departure and arrival axis on the Jet Propulsion Lab (JPL) plots. Two consecutive return opportunities were compared because of the discrepancy between the MAnE results on departure declinations and the JPL plots. This discrepancy was resolved by Andrey Sergeyevsky at JPL — there is an error in the JPL plots in that they are referenced to the Earth's coordinate system instead of Mars.[12]

Table 20. Verification trajectories.

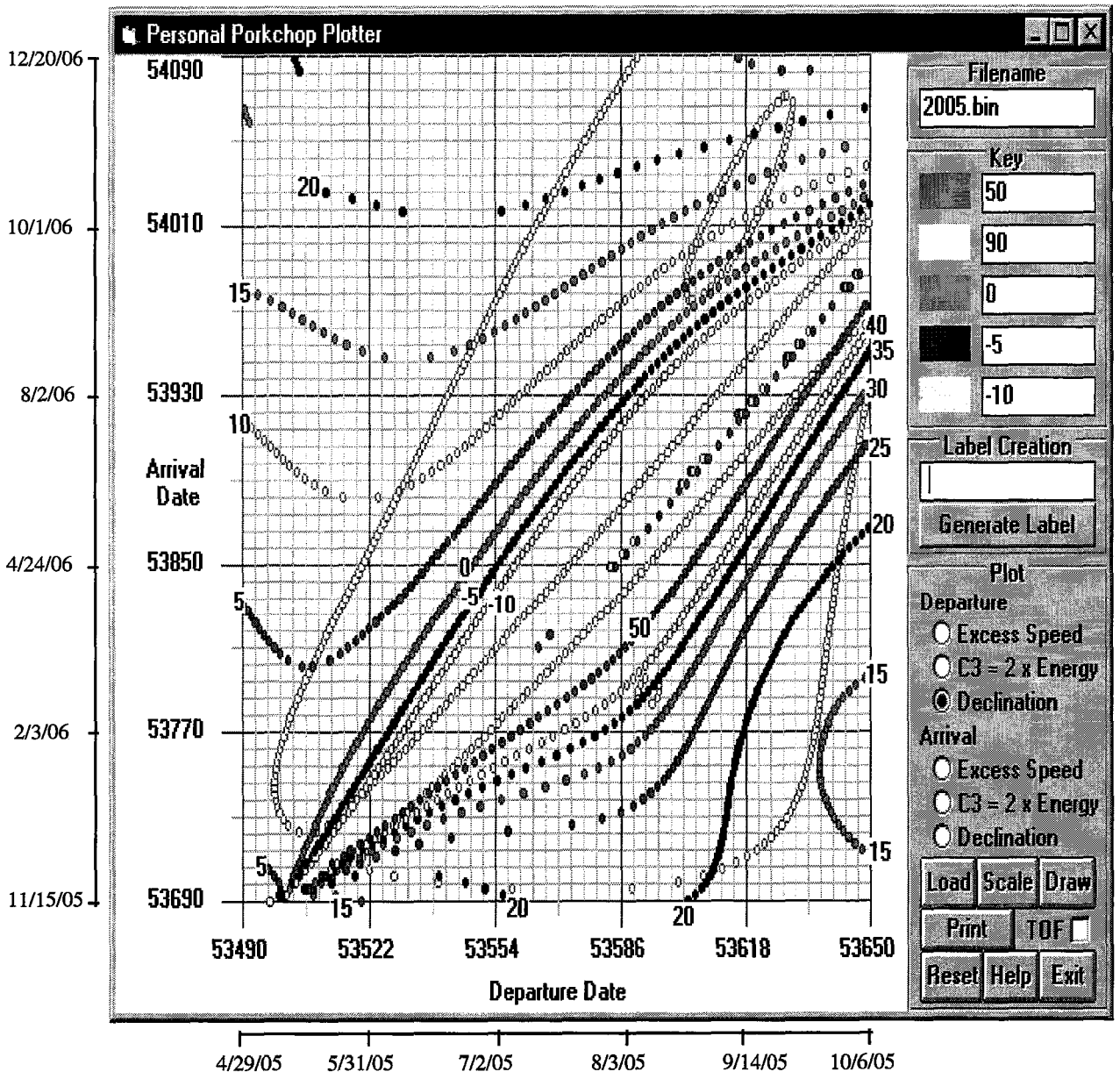
Mission Type	Launch Year	TMI Date (m/d/yr)	TMI ΔV (m/sec)	Arrival Date (m/d/yr)	Outbound Flight Time (days)	Mars Stay Time (days)	Departure Date (m/d/yr)	TEI ΔV (m/sec)	Return Time (days)	Return Date (m/d/yr)	Mission Duration (days)	Mission ΔV (TMI+TEI) (m/sec)	% Diff
Cargo	2001	4/15/01	3,531	1/27/02	287	—	—	—	—	—	—	3,531	—
Verified	2001	4/15/01	3,532	1/27/02	287	—	—	—	—	—	—	3,532	0.028
Cargo	2003	6/7/03	3,574	12/25/03	201	—	—	—	—	—	—	3,574	—
Verified	2003	6/7/03	3,575	12/25/03	201	—	—	—	—	—	—	3,575	0.028
Piloted	2003	6/11/03	3,774	9/18/03	99	689	8/7/05	2,615	120	12/5/05	908	6,389	—
Verified*	2003	6/11/03	4,379	9/18/03	99	689	8/7/05	2,615	120	12/5/05	908	6,994	9.469
Verified	2003	6/11/03	3,774	10/22/03	133	655	8/7/05	2,615	120	12/5/05	908	6,389	0
Cargo	2005	8/11/05	4,009	1/16/06	158	—	—	—	—	—	—	4,009	—
Verified	2005	8/11/05	4,010	1/16/06	158	—	—	—	—	—	—	4,010	0.025
Piloted	2005	8/11/05	4,009	1/16/06	158	572	8/11/07	1,683	187	2/14/08	917	5,692	—
Verified	2005	8/11/05	4,010	1/16/06	158	572	8/11/07	1,683	187	2/14/08	917	5,693	0.018
Cargo	2007	9/13/07	3,759	8/22/08	344	—	—	—	—	—	—	3,759	—
Verified	2007	9/13/07	3,777	8/22/08	344	—	—	—	—	—	—	3,777	0.479
Cargo	2007	9/22/07	3,730	9/25/08	369	—	—	—	—	—	—	3,730	—
Verified	2007	9/22/07	3,749	9/25/08	369	—	—	—	—	—	—	3,749	0.509
Piloted	2007	9/26/07	4,376	2/25/08	152	548	8/26/09	1,336	218	4/1/10	918	5,712	—
Verified	2007	9/26/07	4,372	2/25/08	152	548	8/26/09	1,346	218	4/1/10	918	5,718	0.105
Cargo	2009	10/13/09	3,640	8/29/10	320	—	—	—	—	—	—	3,640	—
Verified	2009	10/13/09	3,642	8/29/10	320	—	—	—	—	—	—	3,642	0.055
Cargo	2009	10/14/09	3,639	8/26/10	316	—	—	—	—	—	—	3,639	—
Verified	2009	10/14/09	3,644	8/26/10	316	—	—	—	—	—	—	3,644	0.137
Piloted	2009	10/22/09	3,948	5/10/10	200	488	9/10/11	1,004	242	5/9/12	930	4,952	—
Verified	2009	10/22/09	3,967	5/10/10	200	488	9/10/11	1,005	242	5/9/12	930	4,972	0.404
Piloted	2009	10/30/09	4,049	4/28/10	180	540	10/20/11	1,833	180	4/17/12	900	5,882	—
Verified	2009	10/30/09	4,065	4/28/10	180	540	10/20/11	1,789	180	4/17/12	900	5,854	0.476
Cargo	2011	11/8/11	3,561	8/31/12	297	—	—	—	—	—	—	3,561	—
Verified	2011	11/8/11	3,581	8/31/12	297	—	—	—	—	—	—	3,581	0.562
Cargo	2011	12/2/11	3,610.6	9/27/12	300	—	—	—	—	—	—	3,611	—
Verified	2011	12/2/11	3,887.0	9/27/12	300	—	—	—	—	—	—	3,887	7.655
Piloted	2011	12/9/11	3,930	6/6/12	180	540	11/28/13	1,520	180	5/27/14	900	5,450	—
Verified	2011	12/9/11	3,935	6/6/12	180	540	11/28/13	1,525	180	5/27/14	900	5,460	0.183
Piloted	2011	12/20/11	4,264	5/27/12	159	492	10/1/13	821	256	6/14/14	907	5,085	—
Verified	2011	12/20/11	4,266	5/27/12	159	492	10/1/13	823	256	6/14/14	907	5,089	0.069
Piloted	2014	1/11/14	3,801	6/20/14	160	545	12/17/15	822	214	7/18/16	919	4,623	—
Verified	2014	1/11/14	3,823	6/20/14	160	545	12/17/15	822	214	7/18/16	919	4,645	0.476
Piloted	2016	3/12/16	3,909	7/20/16	130	631	4/12/18	1,206	145	9/4/18	906	5,115	—
Verified	2016	3/12/16	3,911	7/20/16	130	631	4/12/18	1,207	145	9/4/18	906	5,118	0.059
Piloted	2018	6/5/18	4,287	9/13/18	100	659	7/3/20	1,816	134	11/14/20	893	6,103	—
Verified	2018	6/5/18	4,289	9/13/18	100	659	7/3/20	1,825	134	11/14/20	893	6,114	0.180
Piloted	2020	8/3/20	4,371	11/21/20	110	621	8/4/22	1,788	172	1/23/23	903	6,159	—
Verified	2020	8/3/20	4,372	11/21/20	110	621	8/4/22	1,784	172	1/23/23	903	6,156	0.049

* Determined this must be an incorrect original trajectory

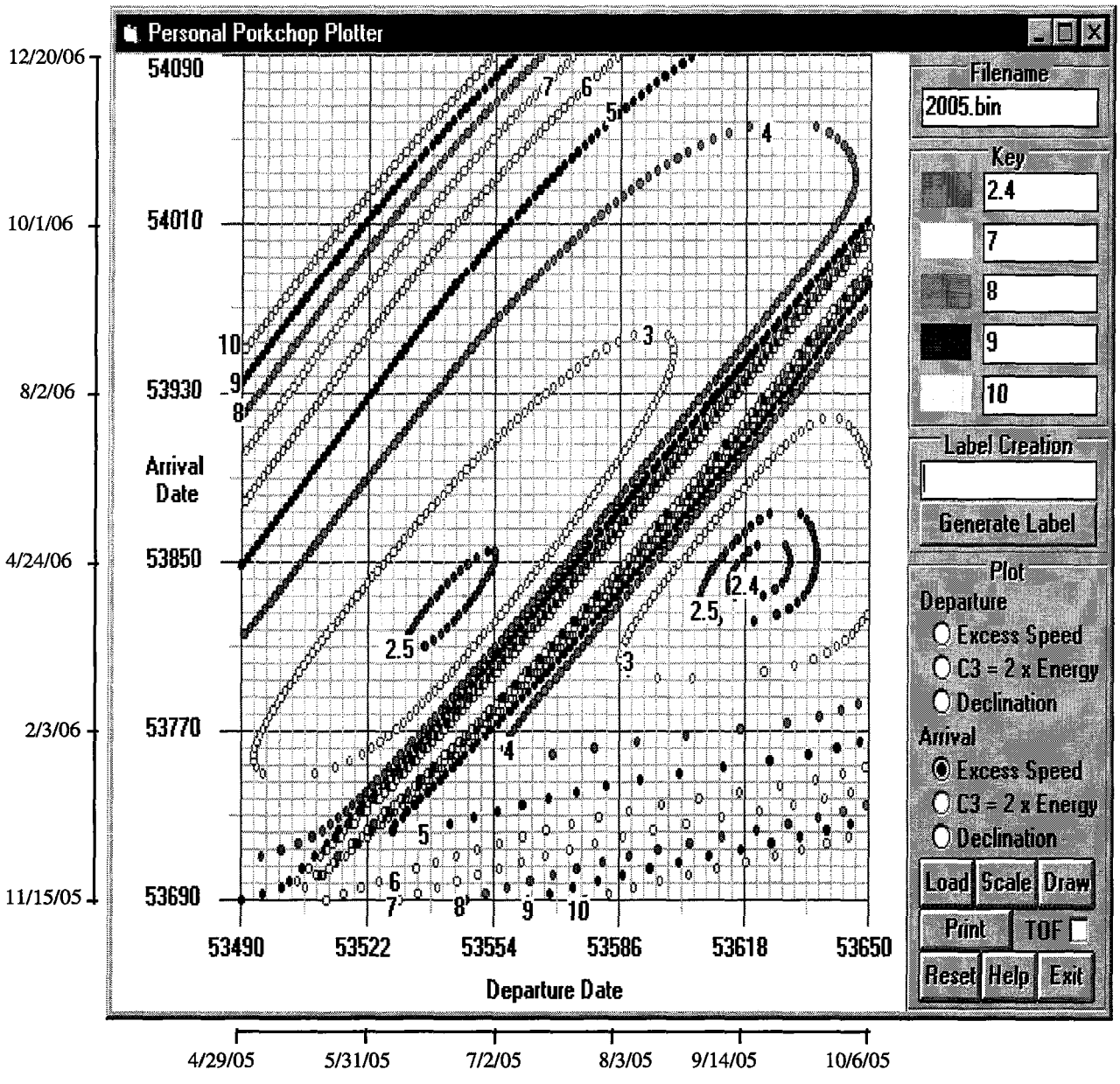
Earth-Mars Trajectories
2005 Conjunction Class
C_3 (Departure Energy) km^2/sec^2



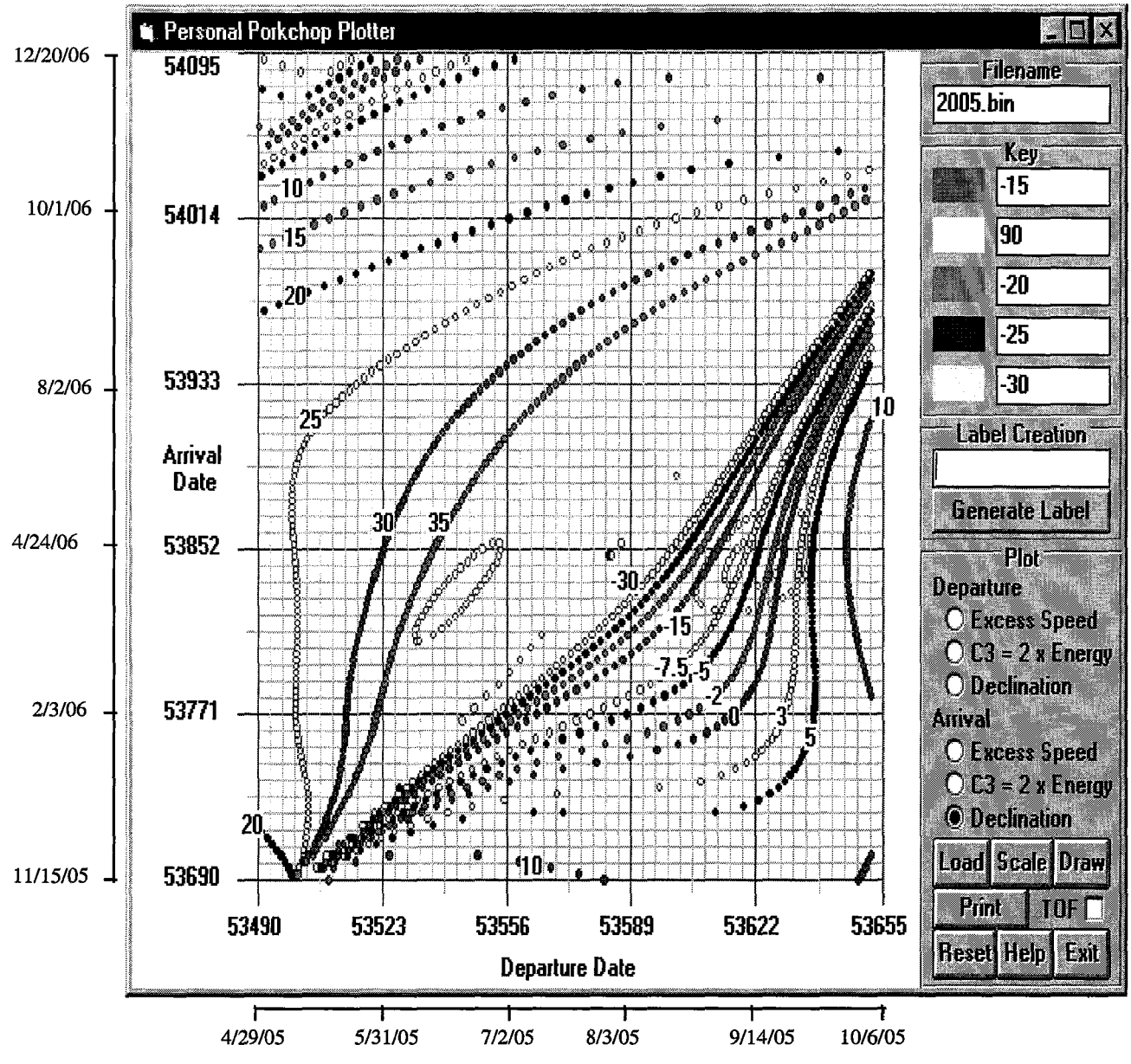
Earth-Mars Trajectories
2005 Conjunction Class
Departure Declination (Degrees)



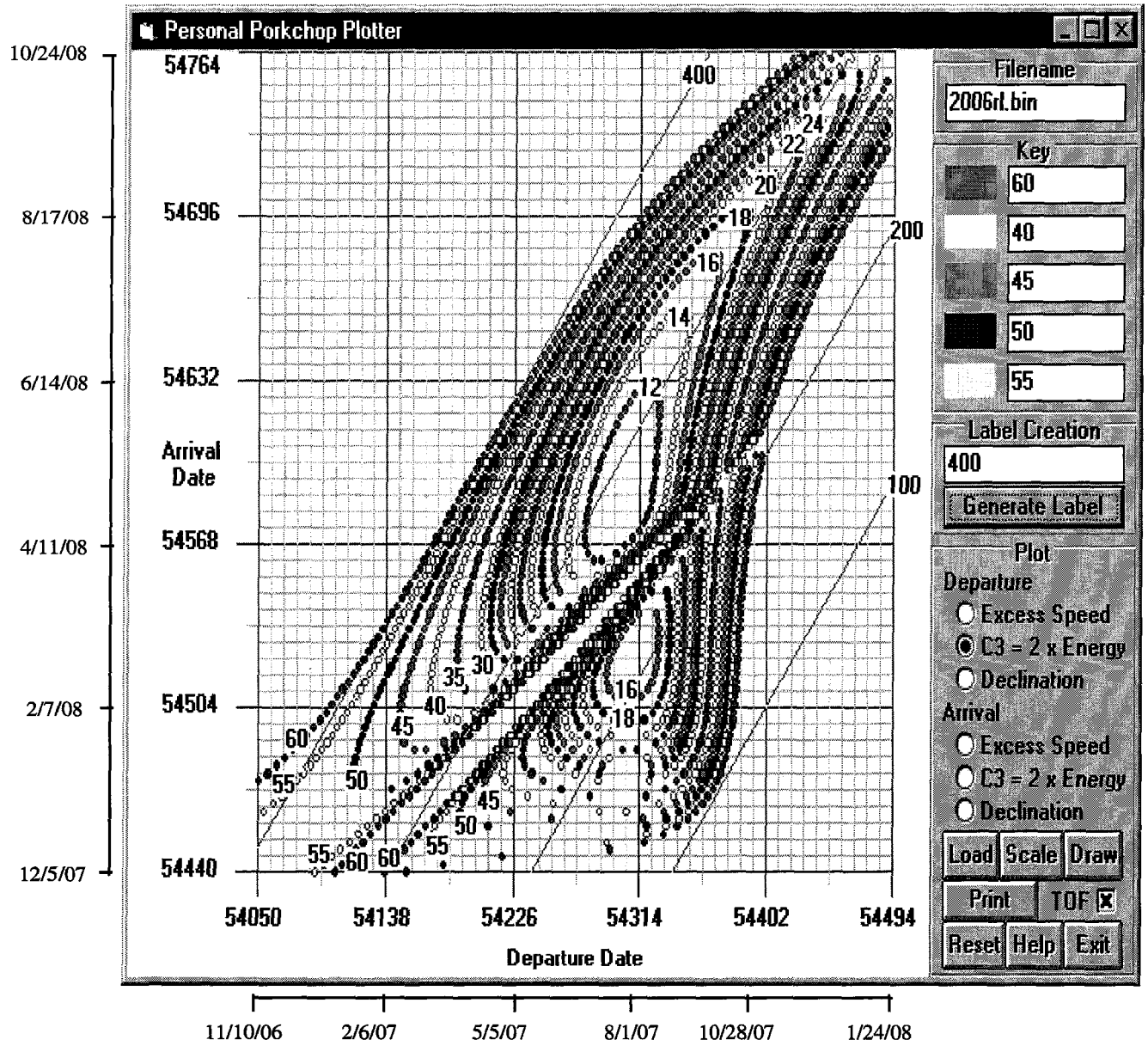
Earth-Mars Trajectories
2005 Conjunction Class
Arrival Excess Speed (km/sec)



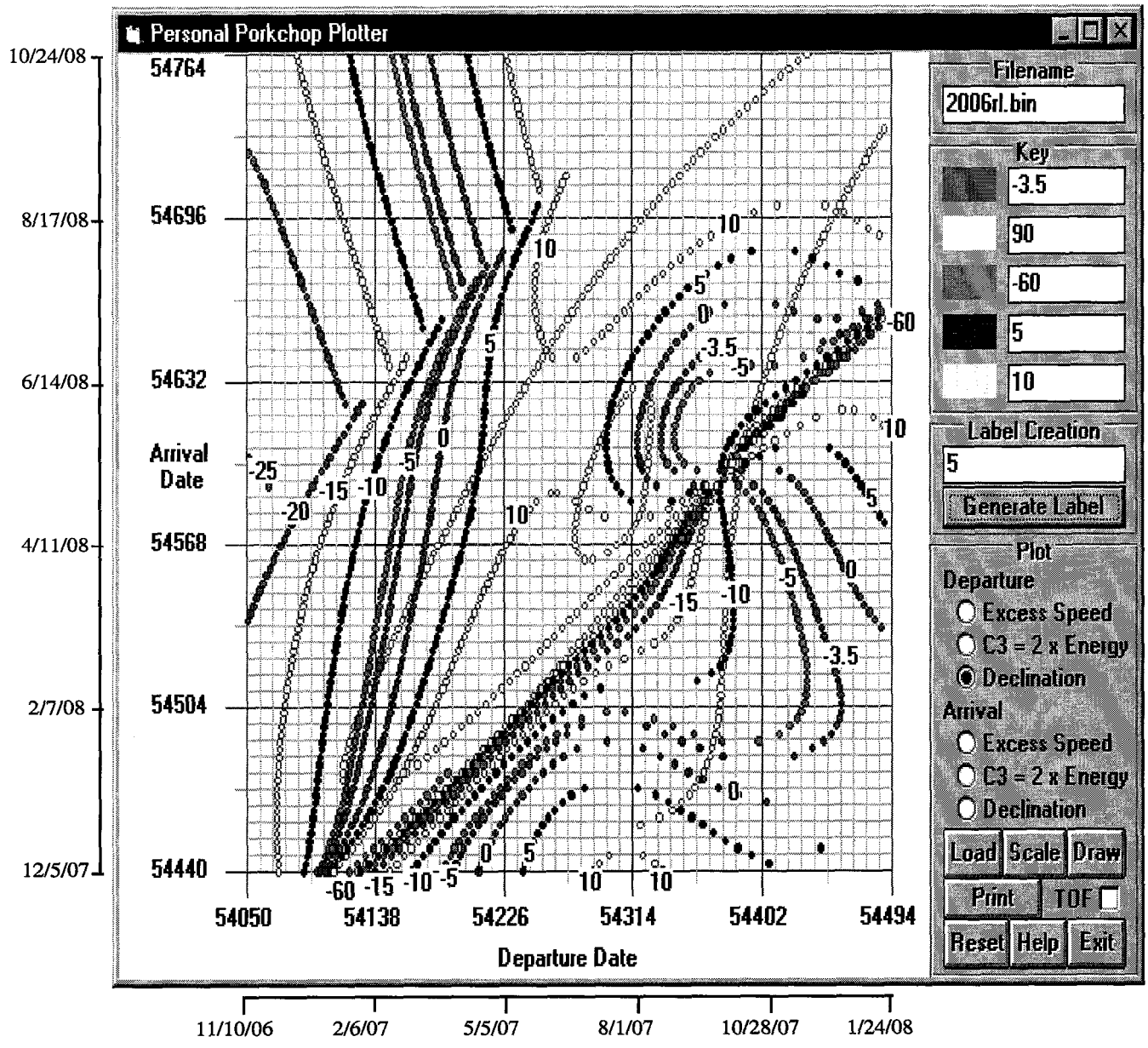
Earth-Mars Trajectories
2005 Conjunction Class
Arrival Declination (Degrees)



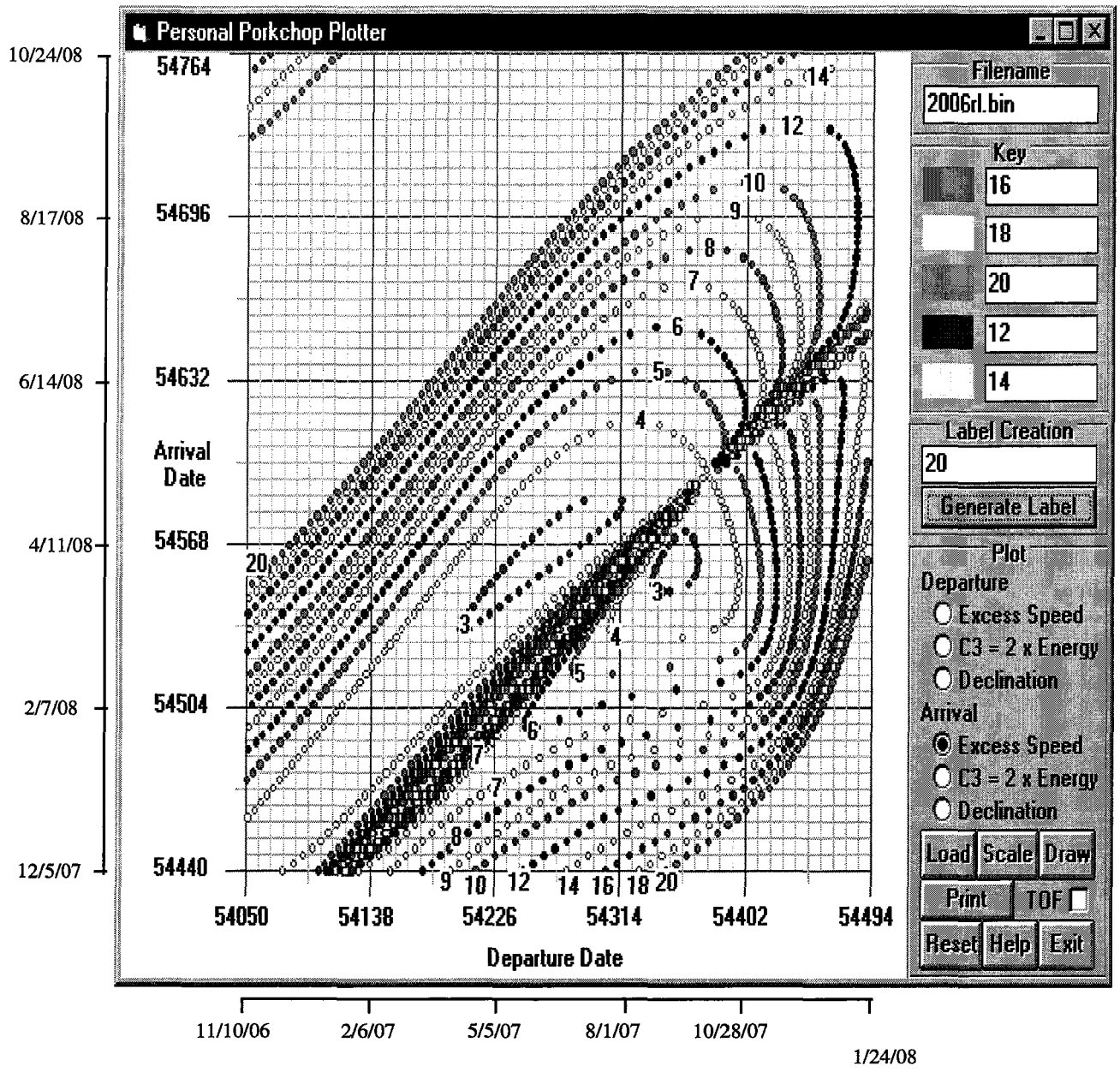
Mars-Earth Trajectories
2006 Conjunction Class
Late Departures
C_3 (Departure Energy) km^2/sec^2



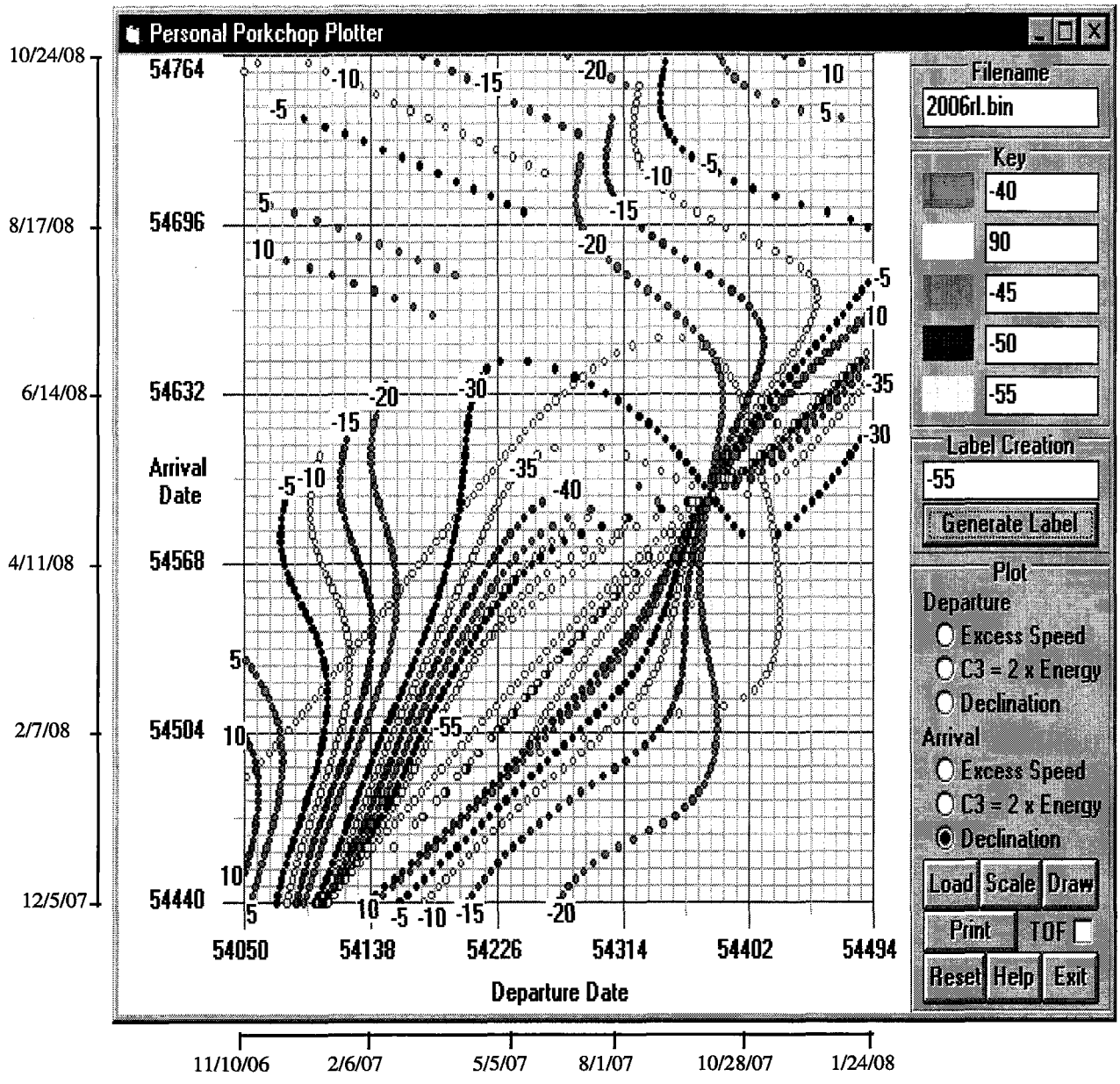
Mars-Earth Trajectories
2006 Conjunction Class
Late Departures
Departure Declination (Degrees)



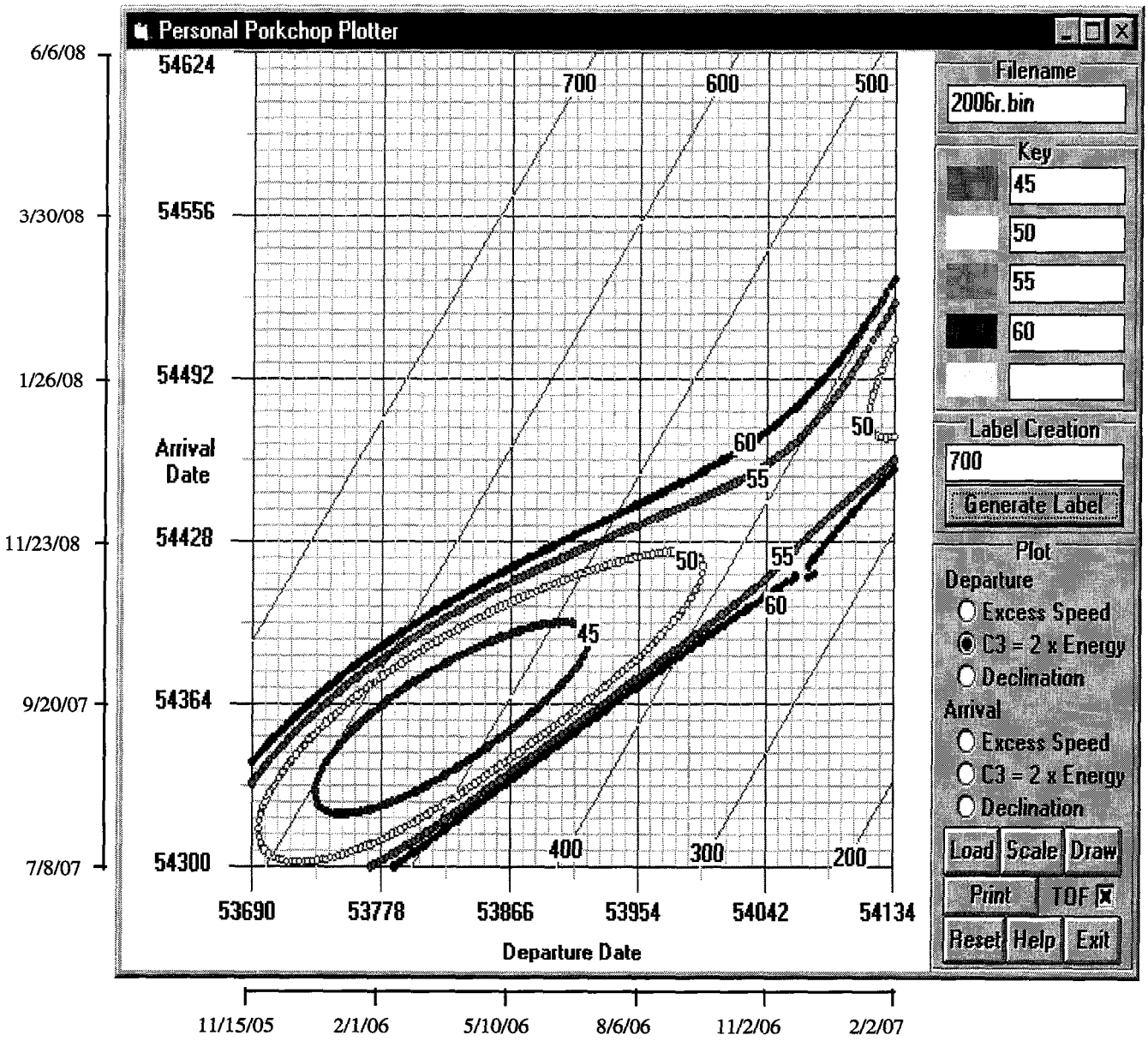
Mars-Earth Trajectories
2006 Conjunction Class
Late Departures
Arrival Excess Speed (km/sec)



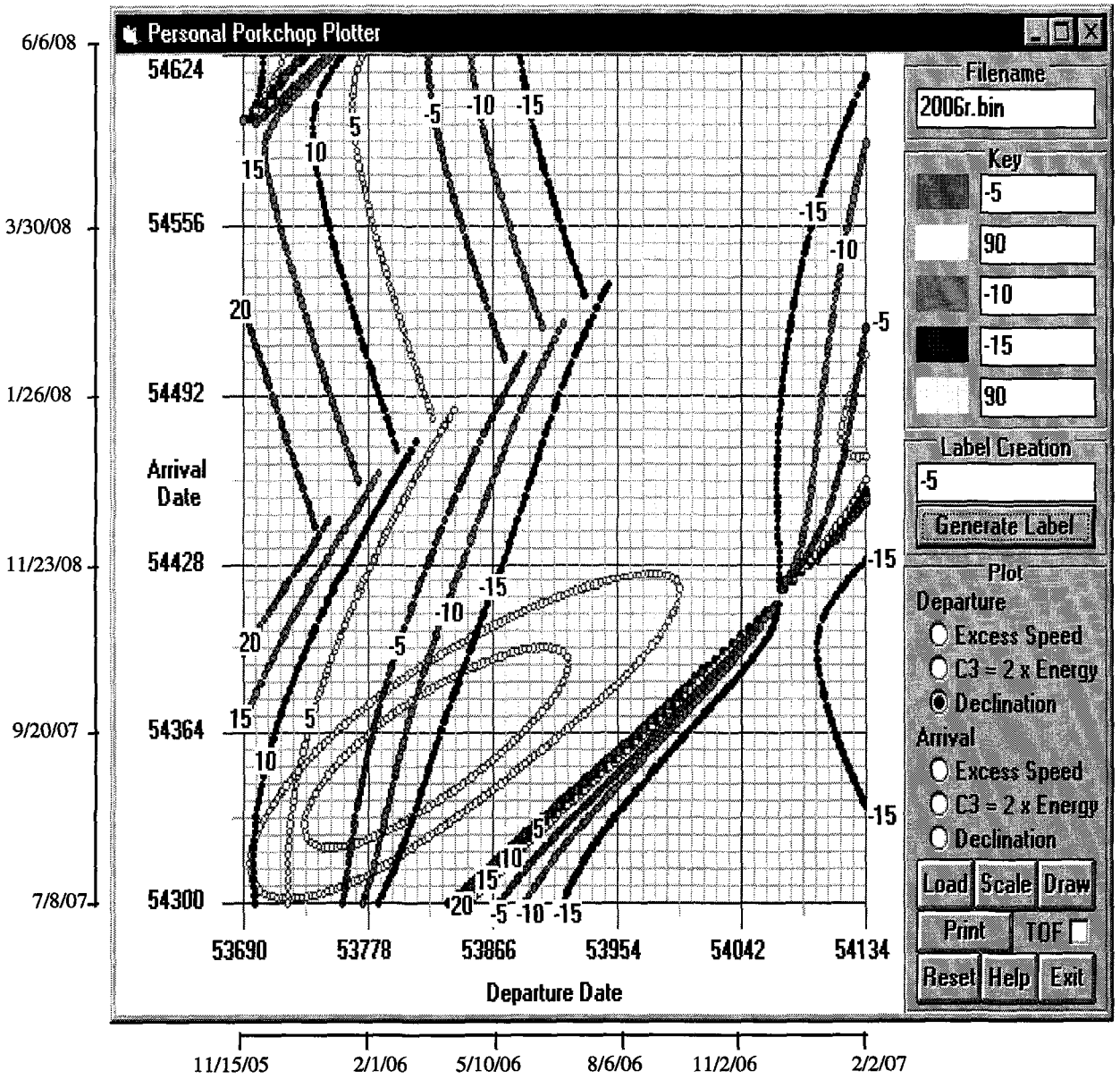
Mars-Earth Trajectories
2006 Conjunction Class
Late Departures
Arrival Declination (Degrees)



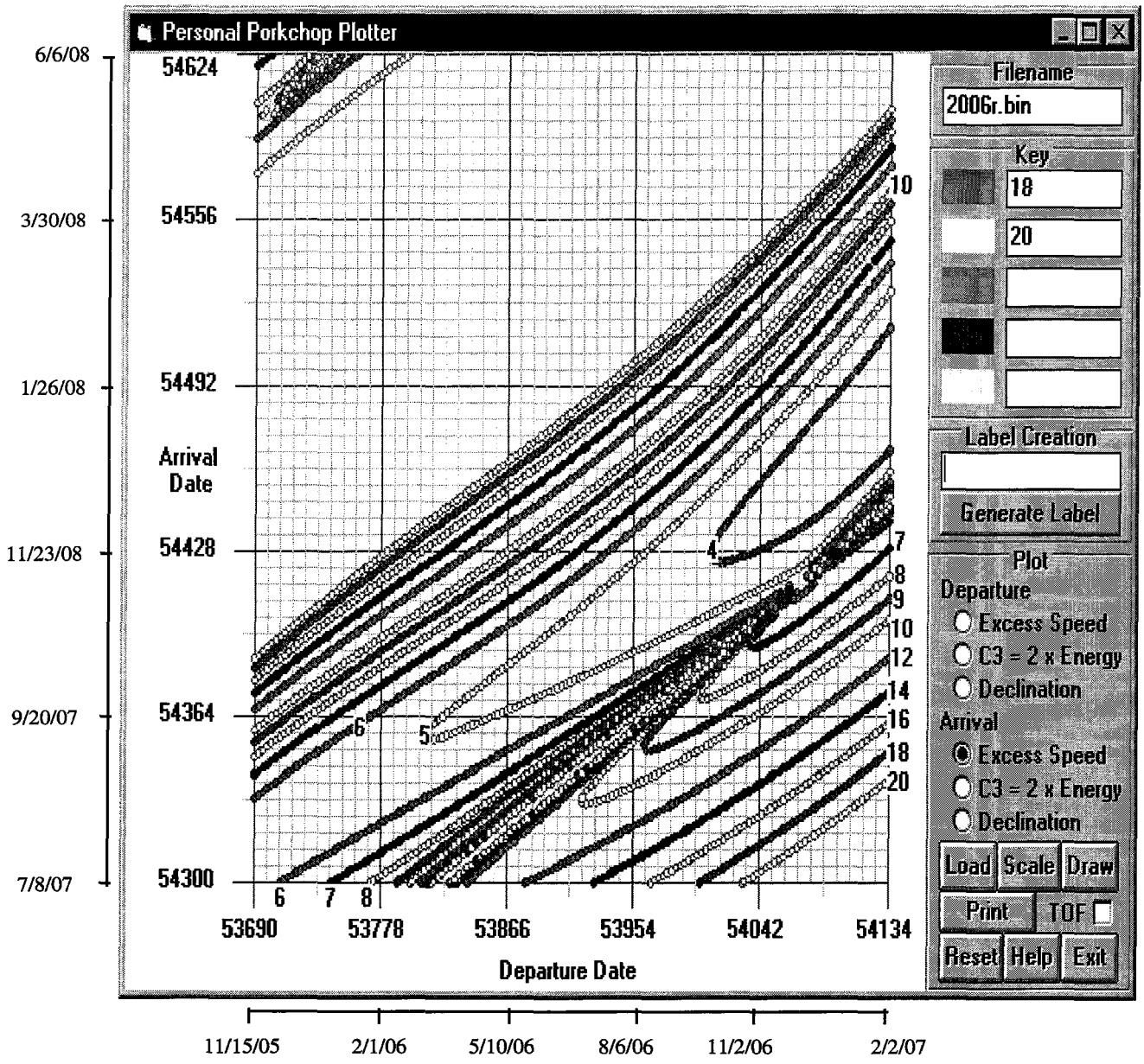
Mars-Earth Trajectories
2006 Conjunction Class
Late Departures
C_3 (Departure Energy) km^2/sec^2



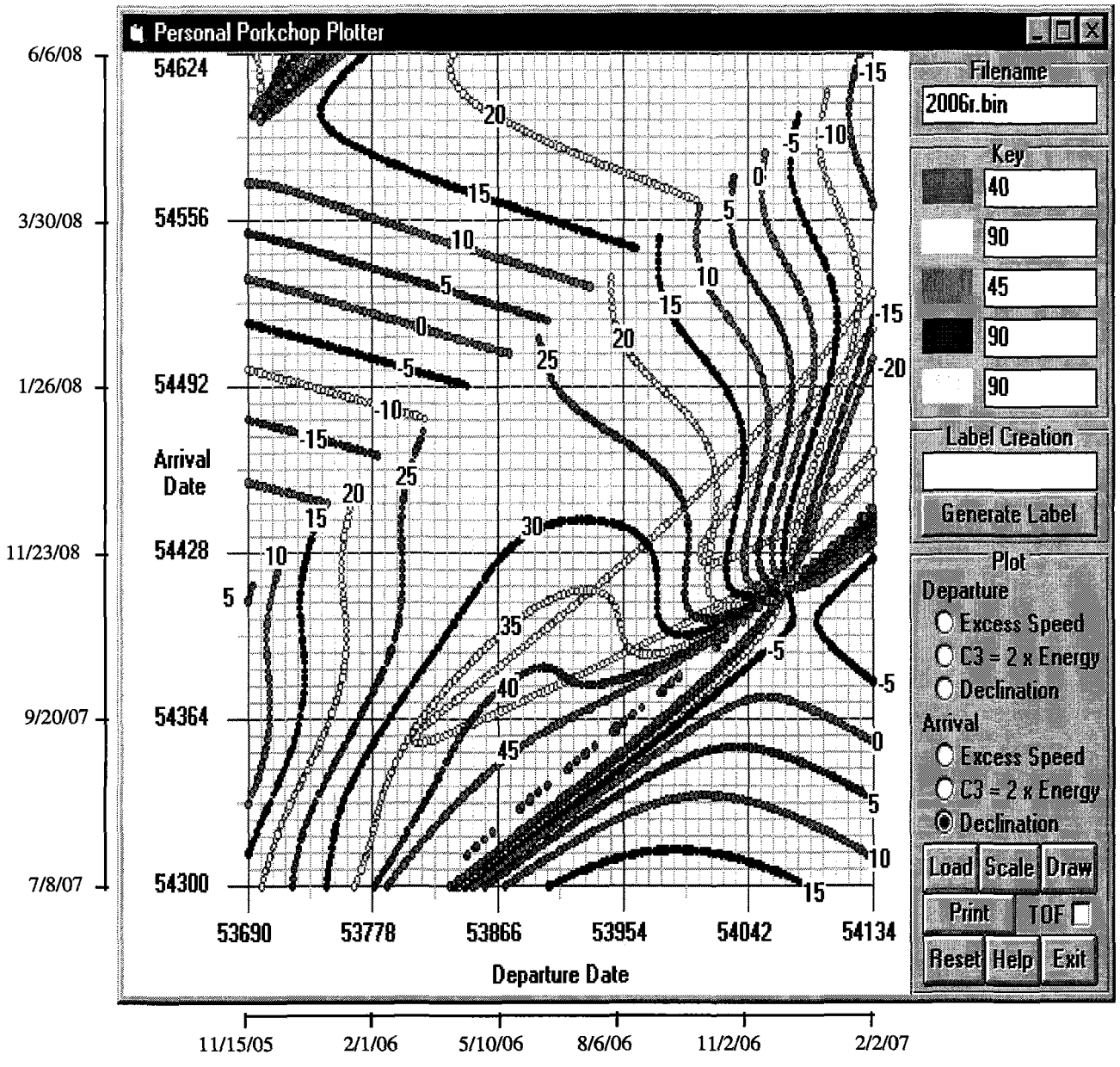
Mars-Earth Trajectories
2006 Conjunction Class
Early Departures
Departure Declination (Degrees)



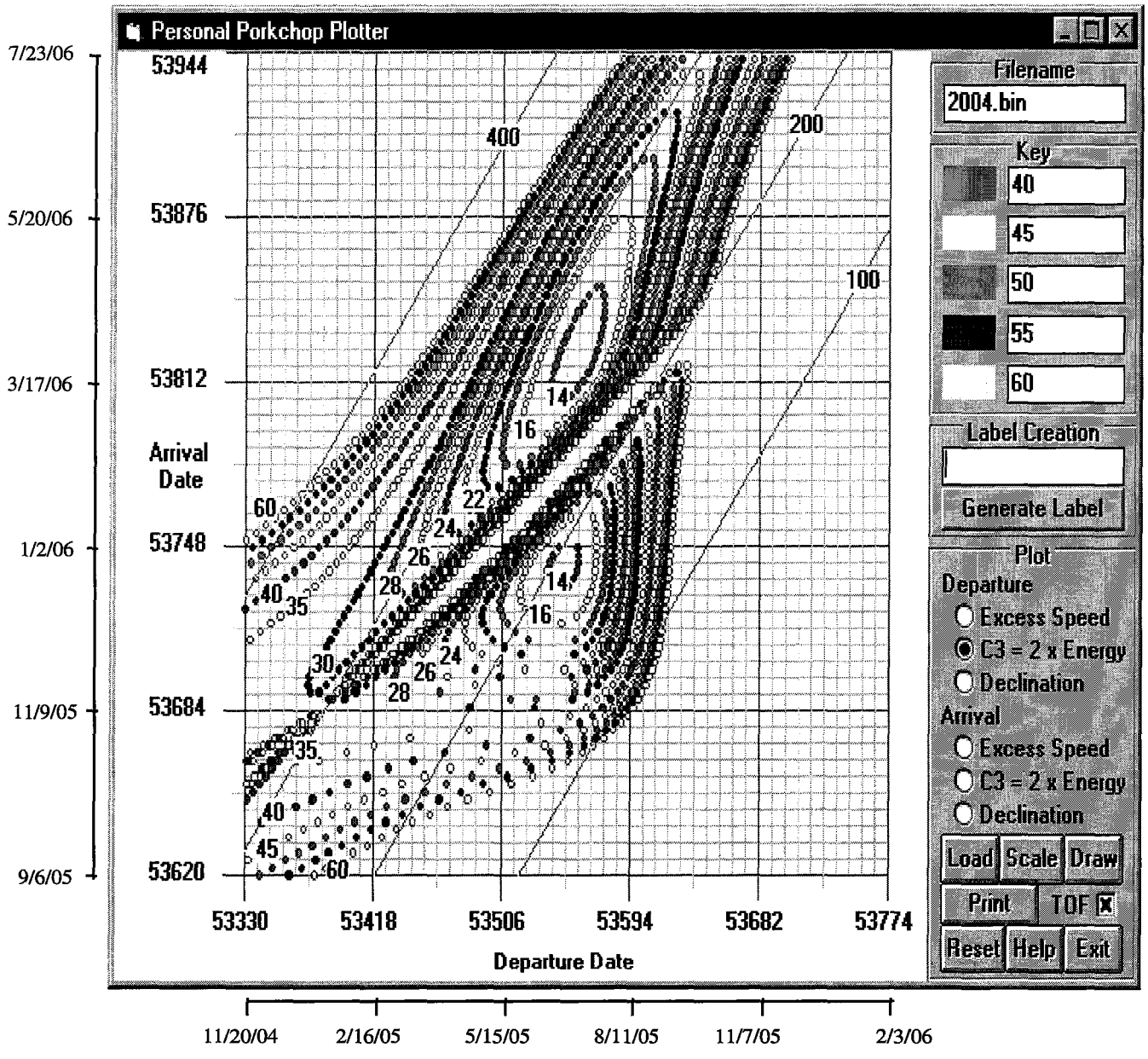
Mars-Earth Trajectories
2006 Conjunction Class
Early Departures
Arrival Excess Speed (km/sec)



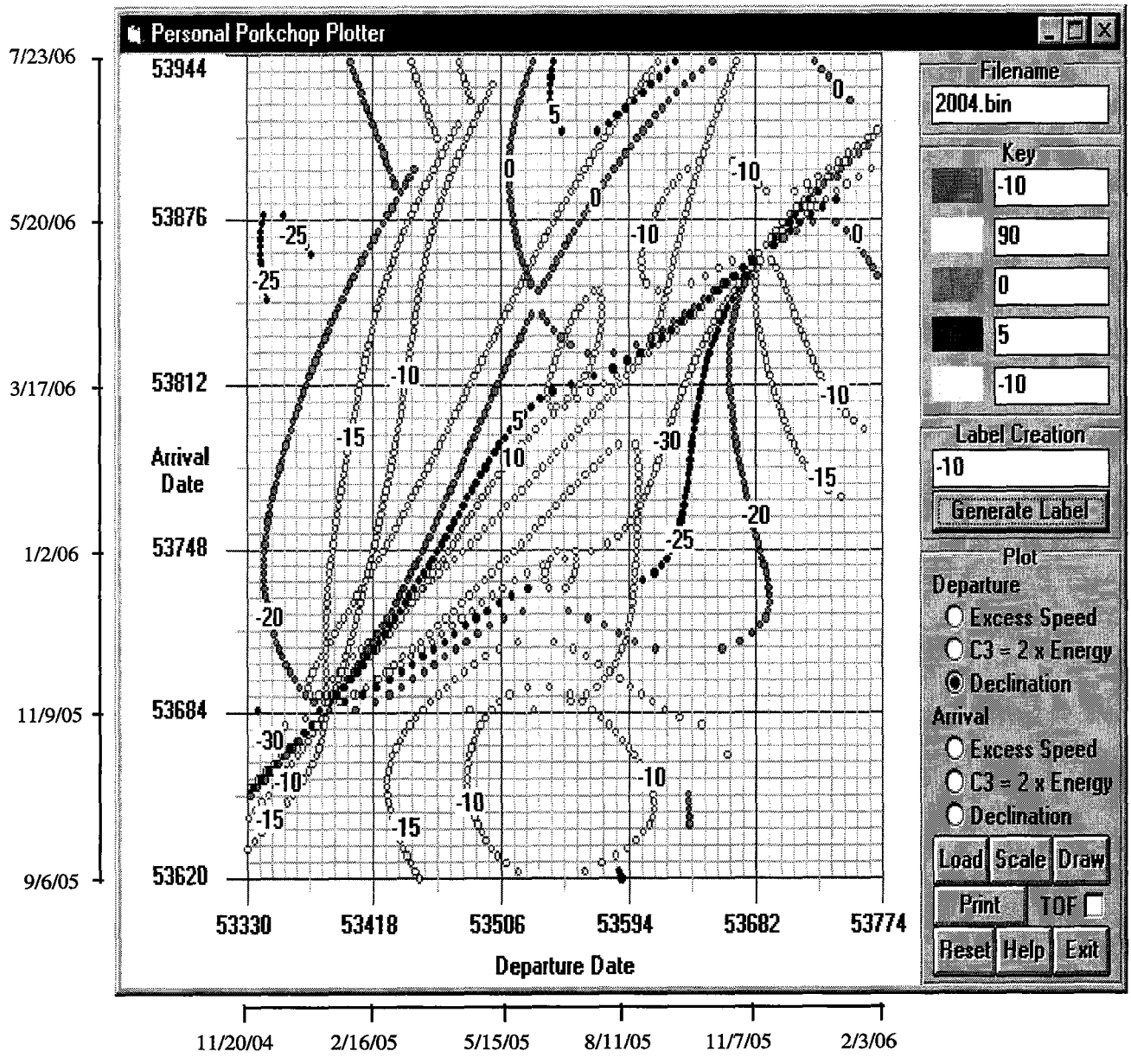
Mars-Earth Trajectories
2006 Conjunction Class
Early Departures
Arrival Declination (Degrees)



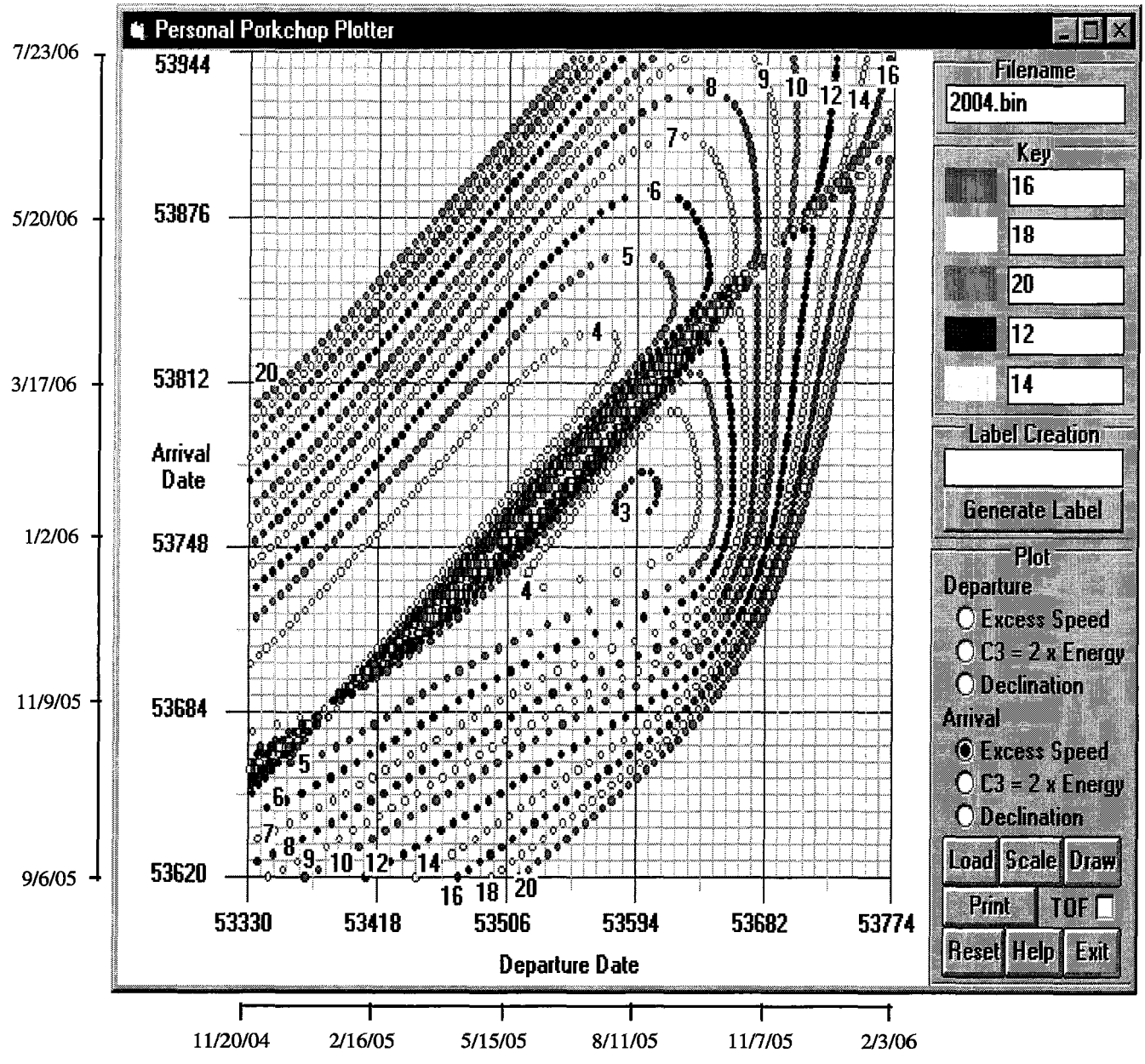
Mars-Earth Trajectories
2004 Conjunction Class
Late Departures
C_3 (Departure Energy) km^2/sec^2



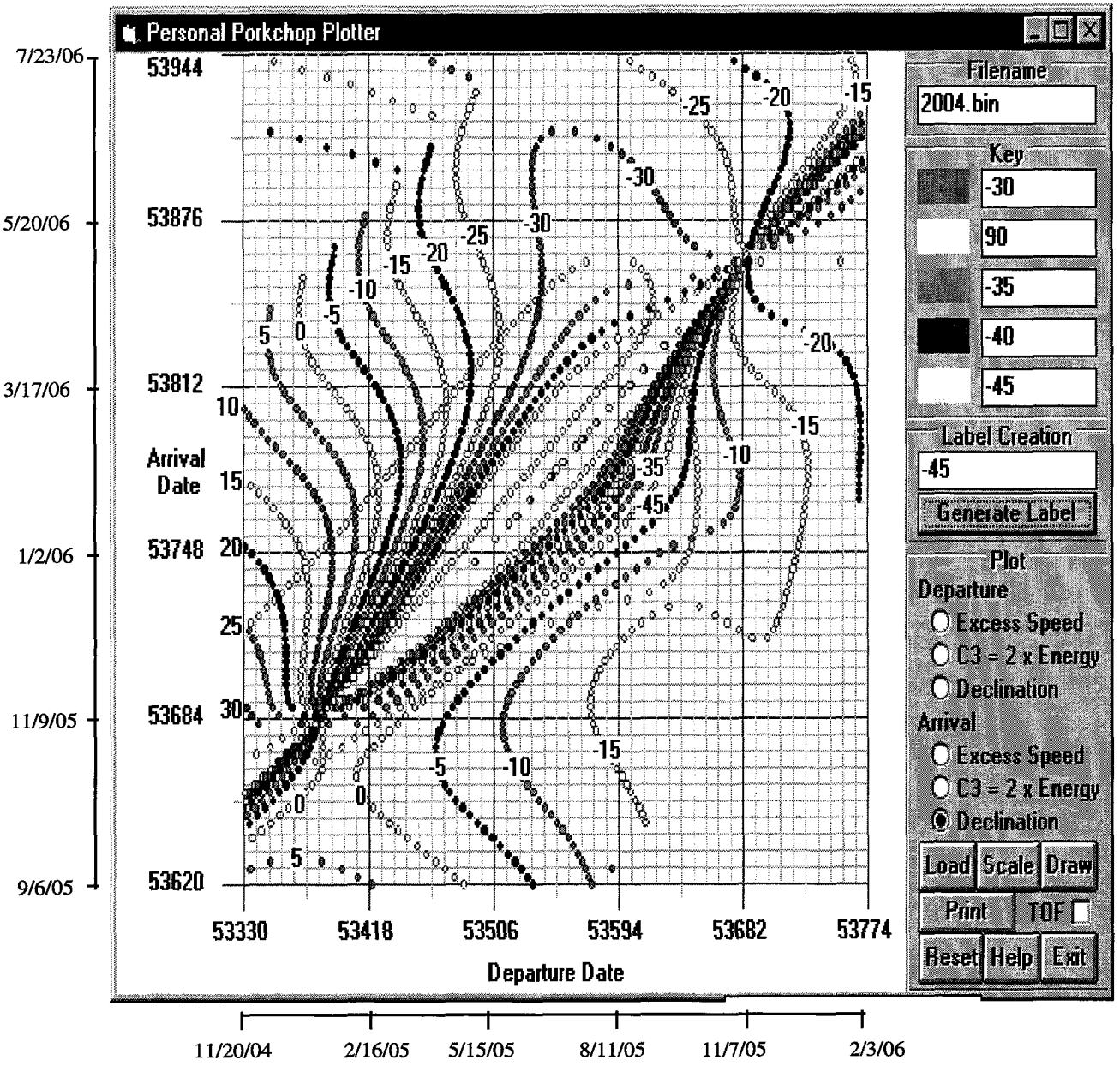
Mars-Earth Trajectories
2004 Conjunction Class
Late Departures
Departure Declination (Degrees)



Mars-Earth Trajectories
2004 Conjunction Class
Late Departures
Arrival Excess Speed (km/sec)



Mars-Earth Trajectories
2004 Conjunction Class
Late Departures
Arrival Declination (Degrees)



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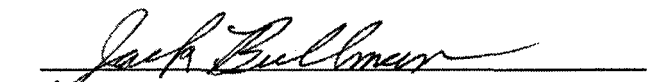
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APPROVAL

INTERPLANETARY MISSION DESIGN HANDBOOK: EARTH-TO-MARS MISSION OPPORTUNITIES AND MARS-TO-EARTH RETURN OPPORTUNITIES 2004–2024

L.E. George and L.D. Kos

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.



A. ROTH
DIRECTOR, PROGRAM DEVELOPMENT DIRECTORATE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operation and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503

1. AGENCY USE ONLY *(Leave Blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	July 1998	Technical Memorandum

4. TITLE AND SUBTITLE
Interplanetary Mission Design Handbook:
Earth-to-Mars Mission Opportunities and
Mars-to-Earth Return Opportunities 2004–2024

5. FUNDING NUMBERS

6. AUTHORS
L.E. George*
L.D. Kos

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

8. PERFORMING ORGANIZATION REPORT NUMBER
M–881

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA/TM—1998–208533

11. SUPPLEMENTARY NOTES
*U.S. Air Force Academy, Colorado Springs, Colorado
Prepared by the Preliminary Design Office, Program Development Directorate

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified—Unlimited
Subject Category 13
Nonstandard Distribution

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This paper provides information for trajectory designers and mission planners to determine Earth-Mars and Mars-Earth mission opportunities for the years 2009–2024. These studies were performed in support of a human Mars mission scenario that will consist of two cargo launches followed by a piloted mission during the next opportunity approximately 2 years later. "Porkchop" plots defining all of these mission opportunities are provided which include departure energy, departure excess speed, departure declination arrival excess speed, and arrival declinations for the mission space surrounding each opportunity. These plots are intended to be directly applicable for the human Mars mission scenario described briefly herein. In addition, specific trajectories and several alternate trajectories are recommended for each cargo and piloted opportunity. Finally, additional studies were performed to evaluate the effect of various thrust-to-weight ratios on gravity losses and total time-of-flight tradeoff, and the resultant propellant savings and are briefly summarized.

14. SUBJECT TERMS
Mars, Mars mission(s), trajectories, mission opportunities, interplanetary missions, interplanetary orbits, interplanetary trajectories

15. NUMBER OF PAGES
162

16. PRICE CODE
A08

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited